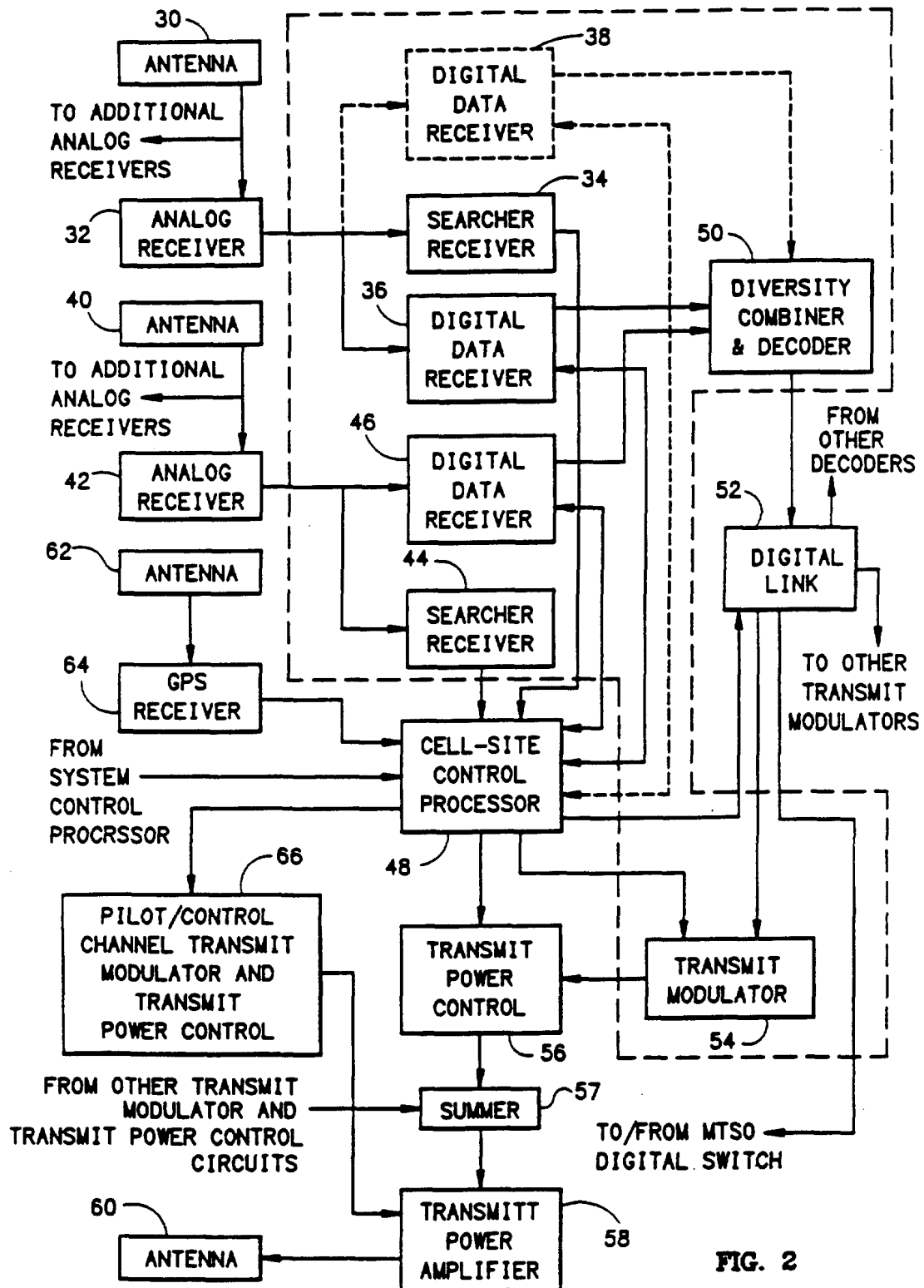


FIG. 1



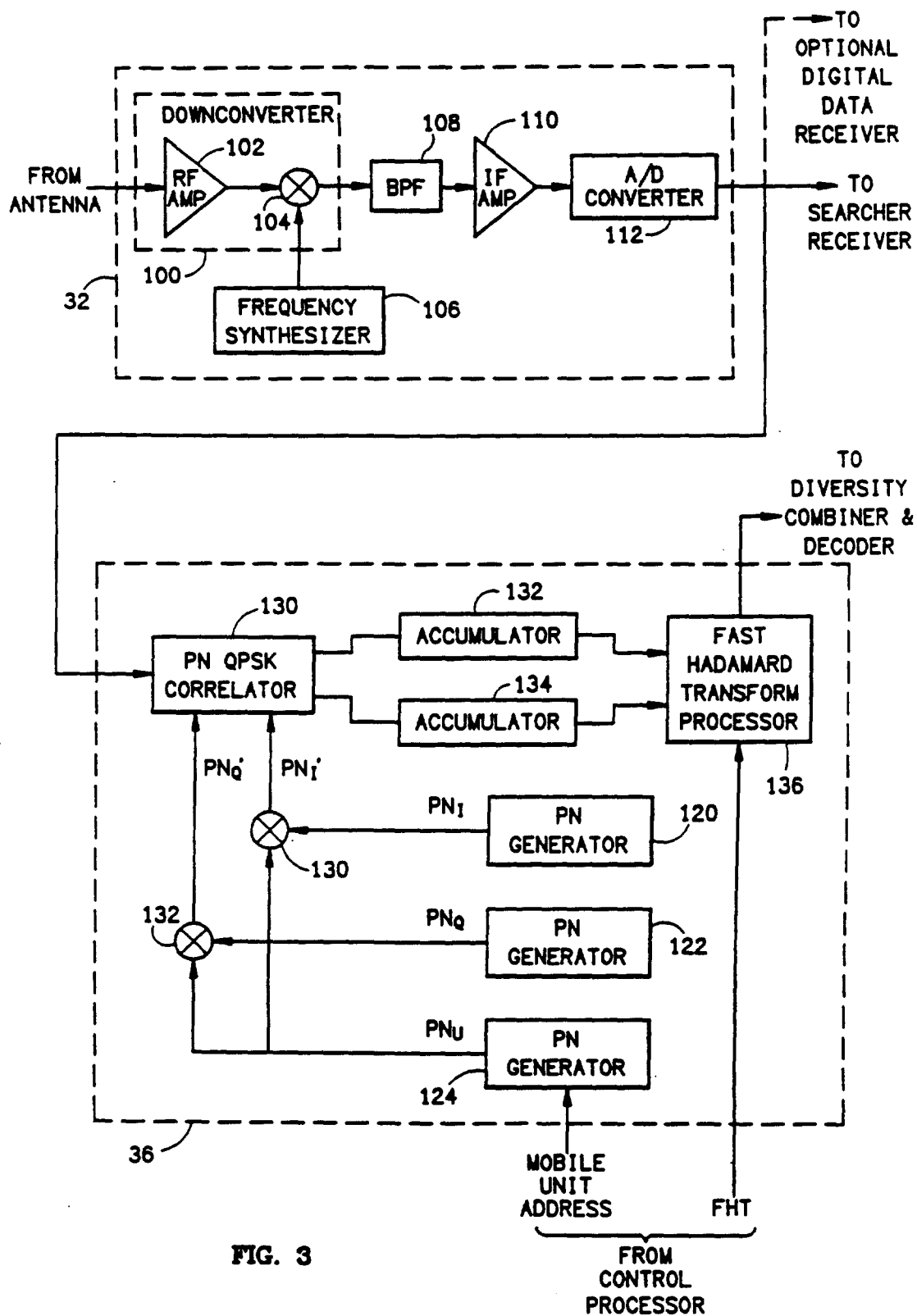
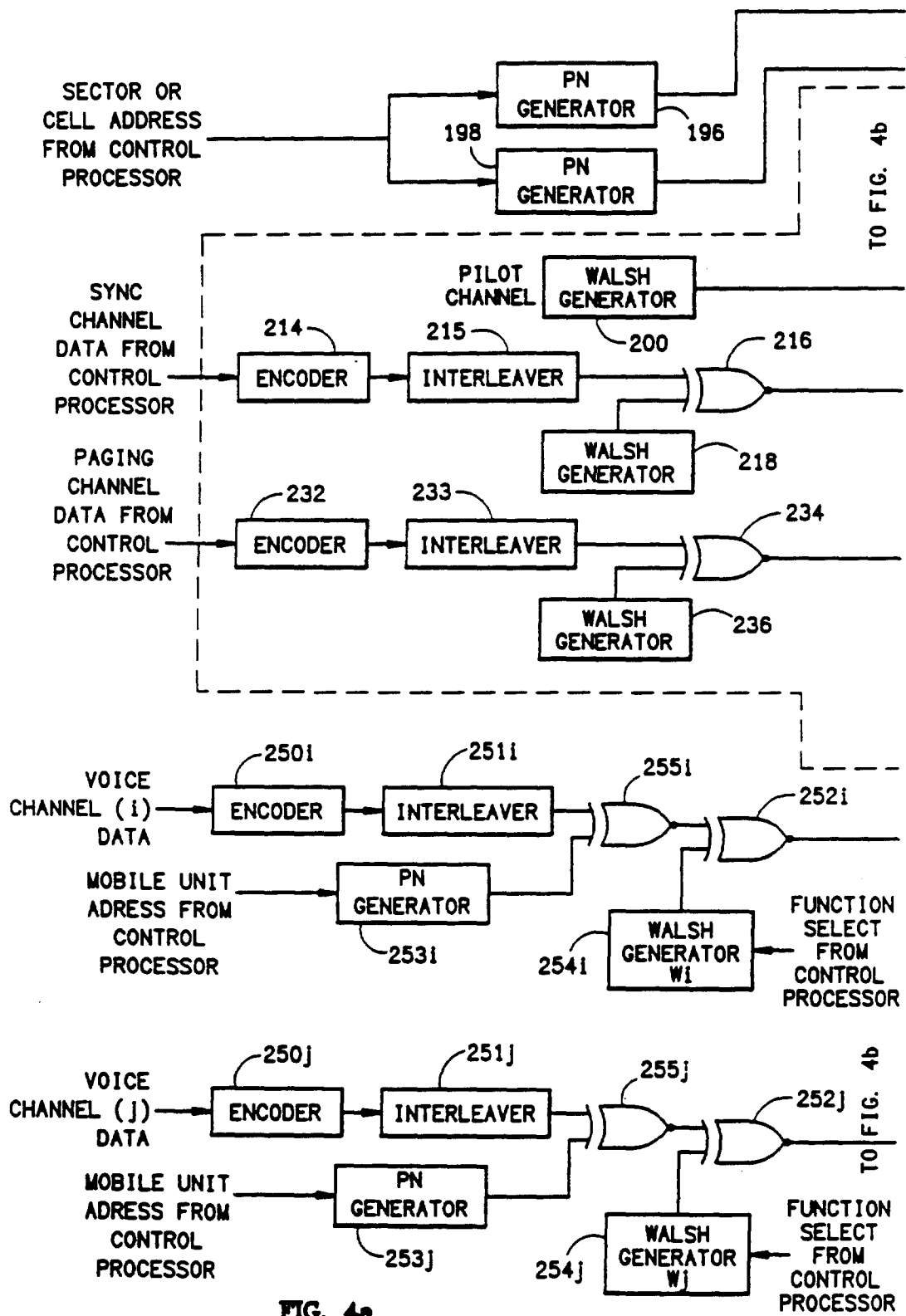


FIG. 3



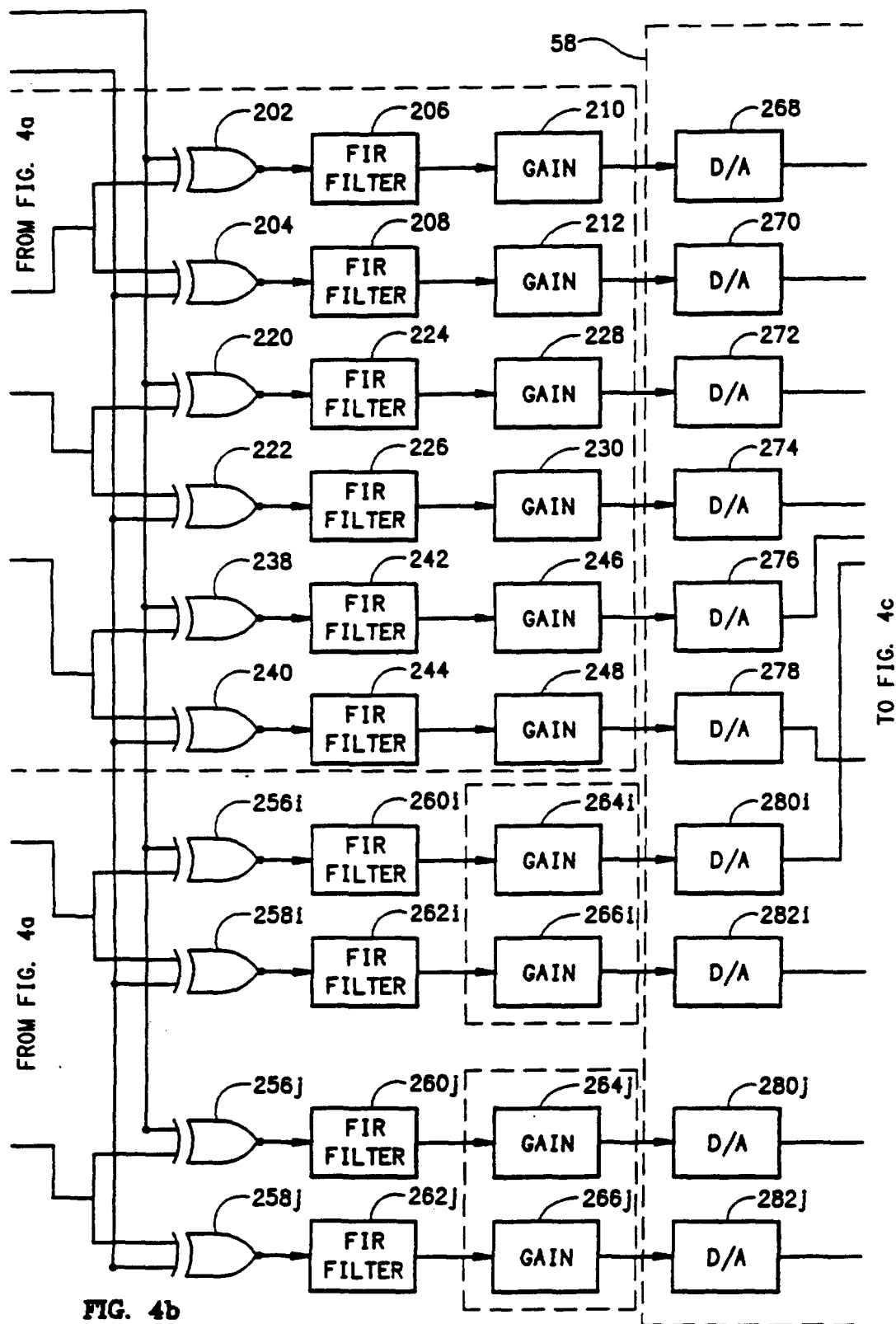
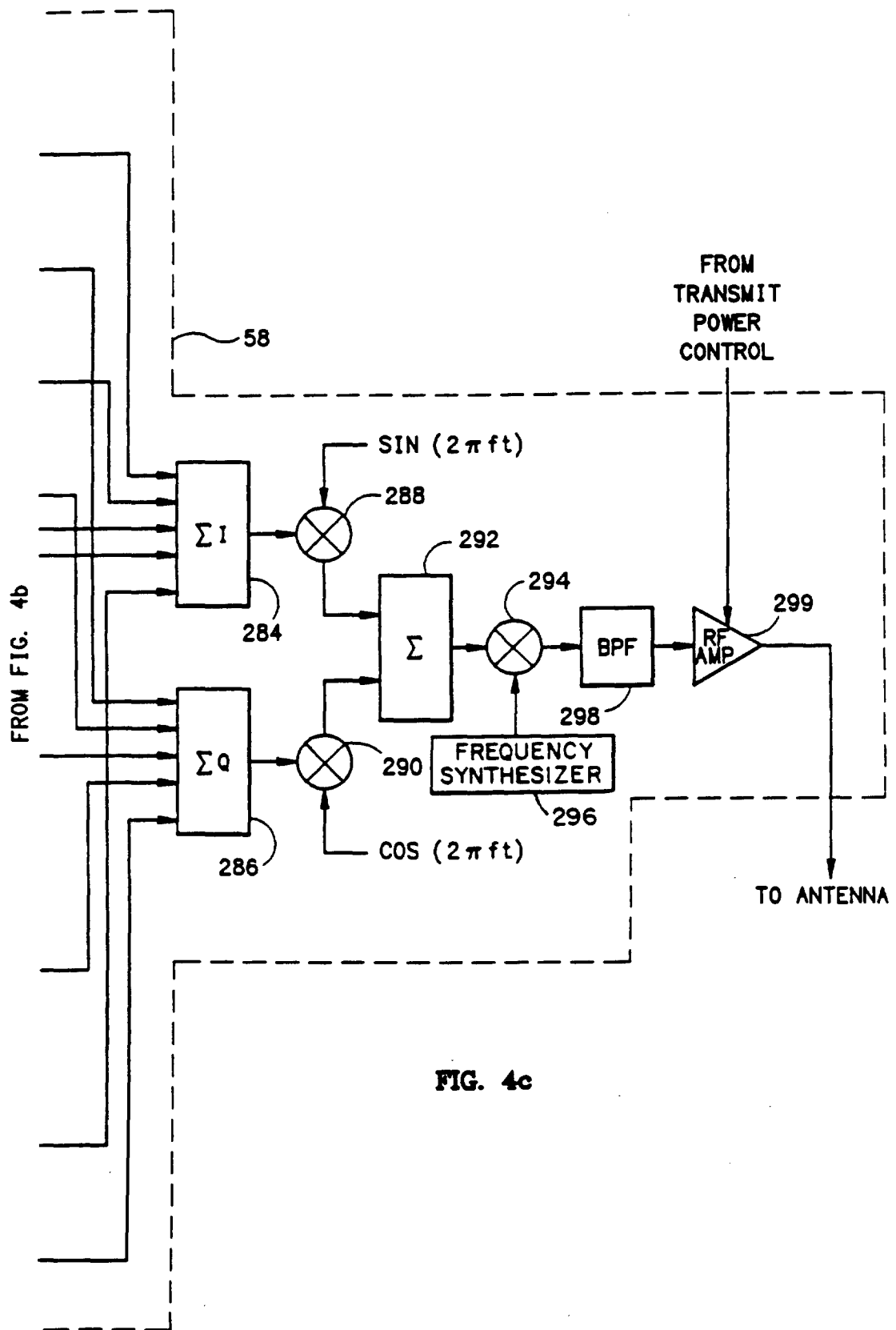


FIG. 4b



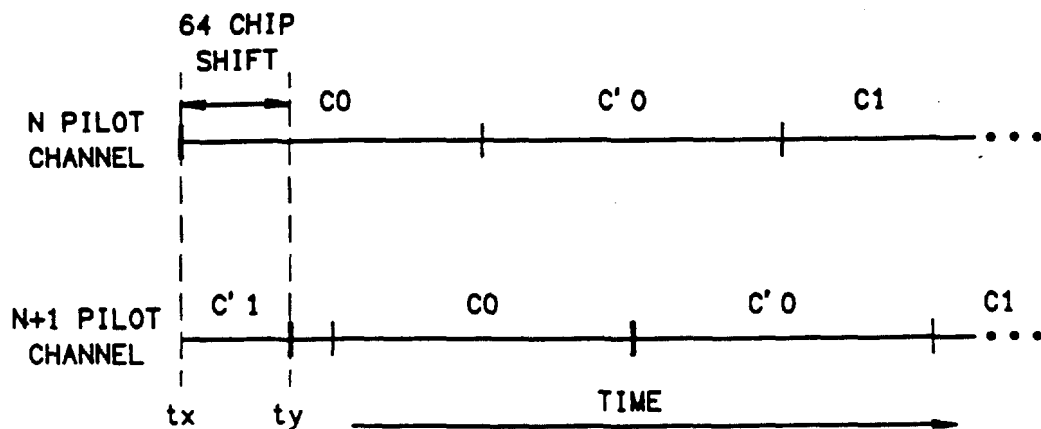


FIG. 5

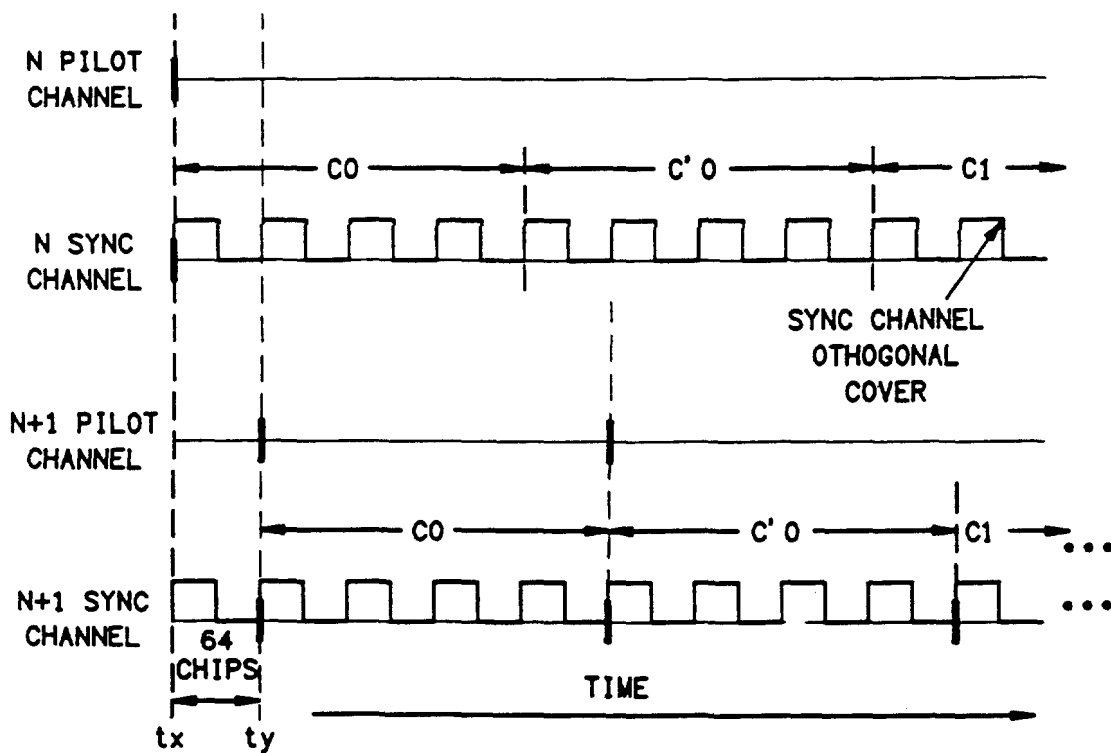


FIG. 6

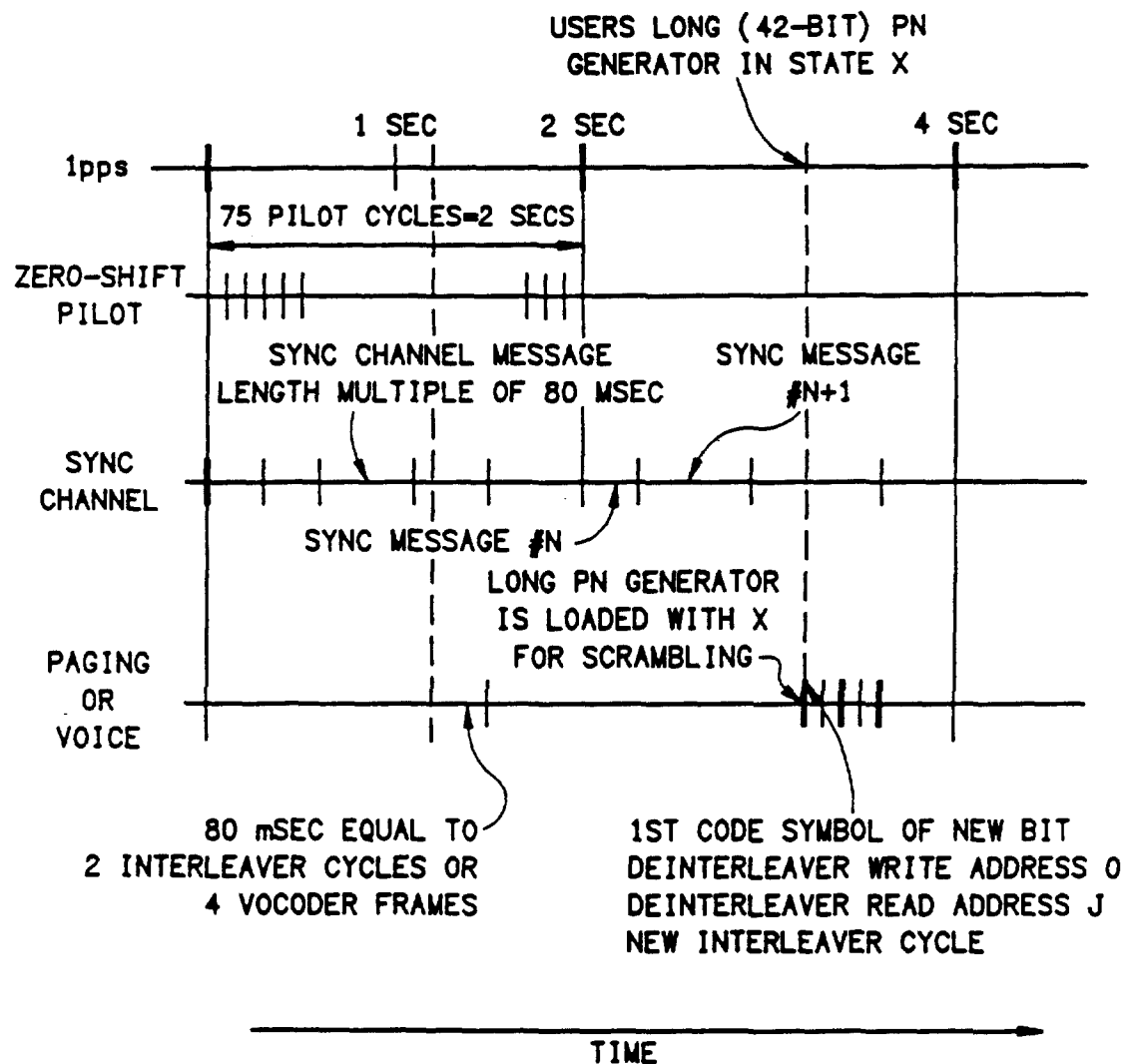


FIG. 7

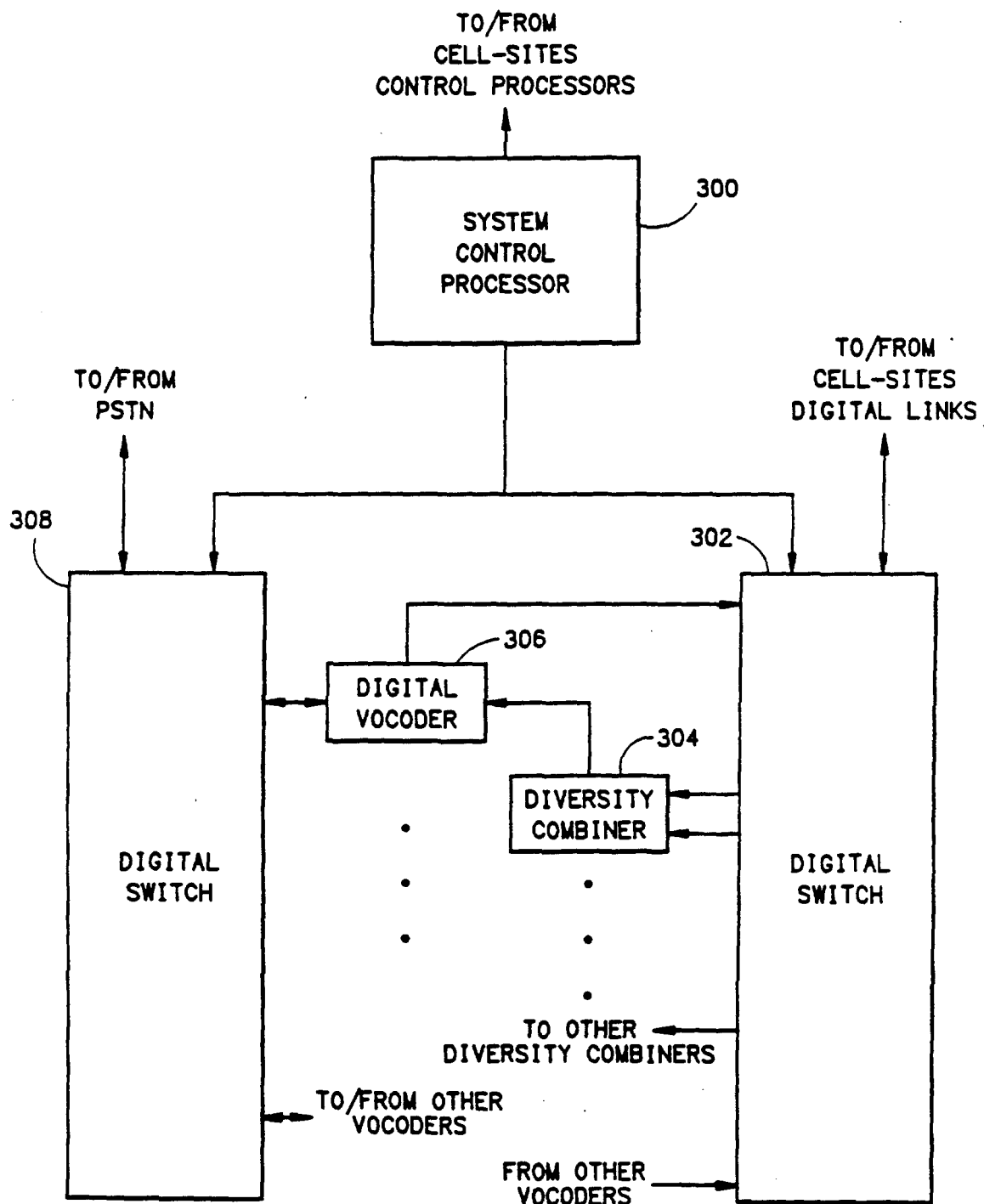
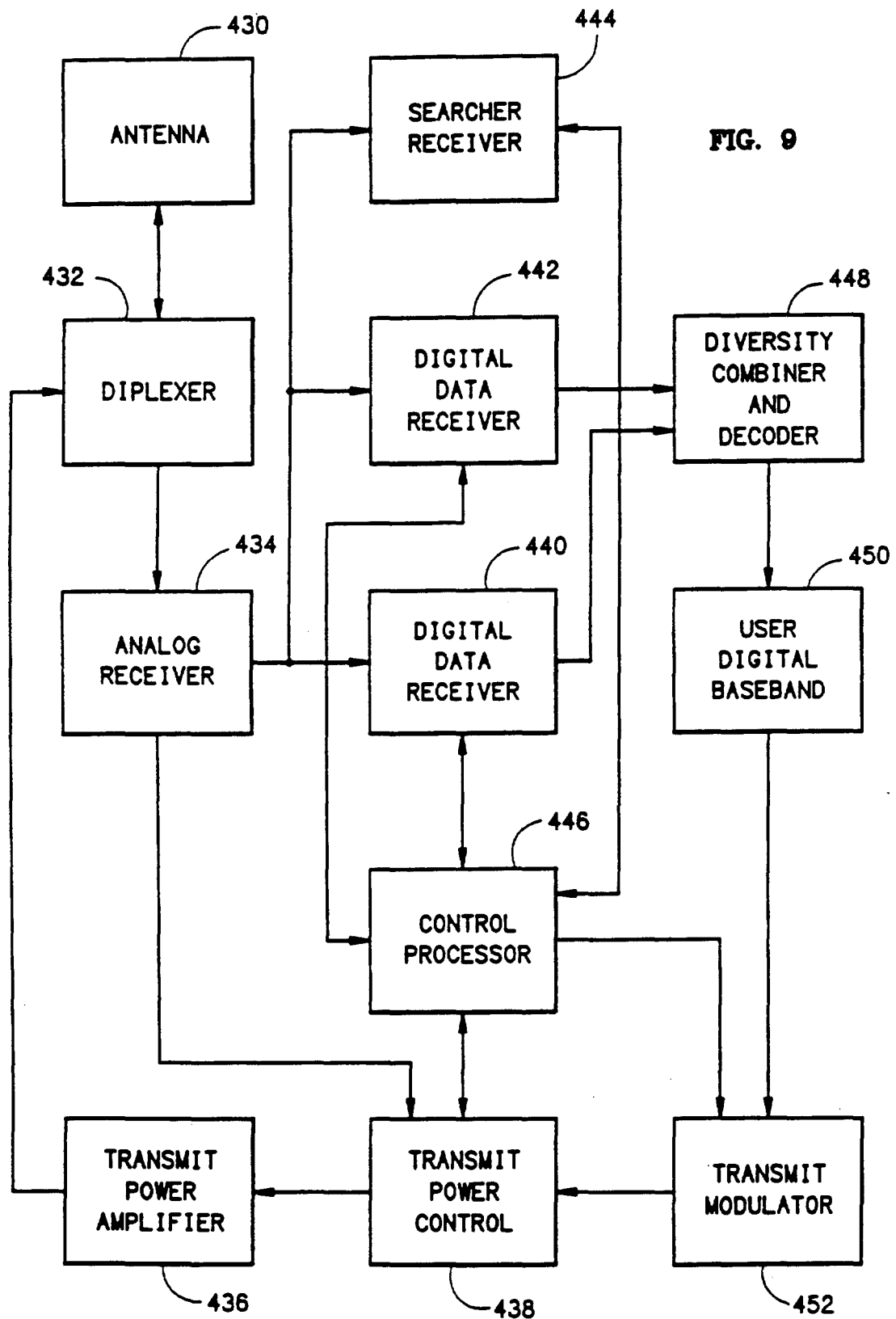


FIG. 8



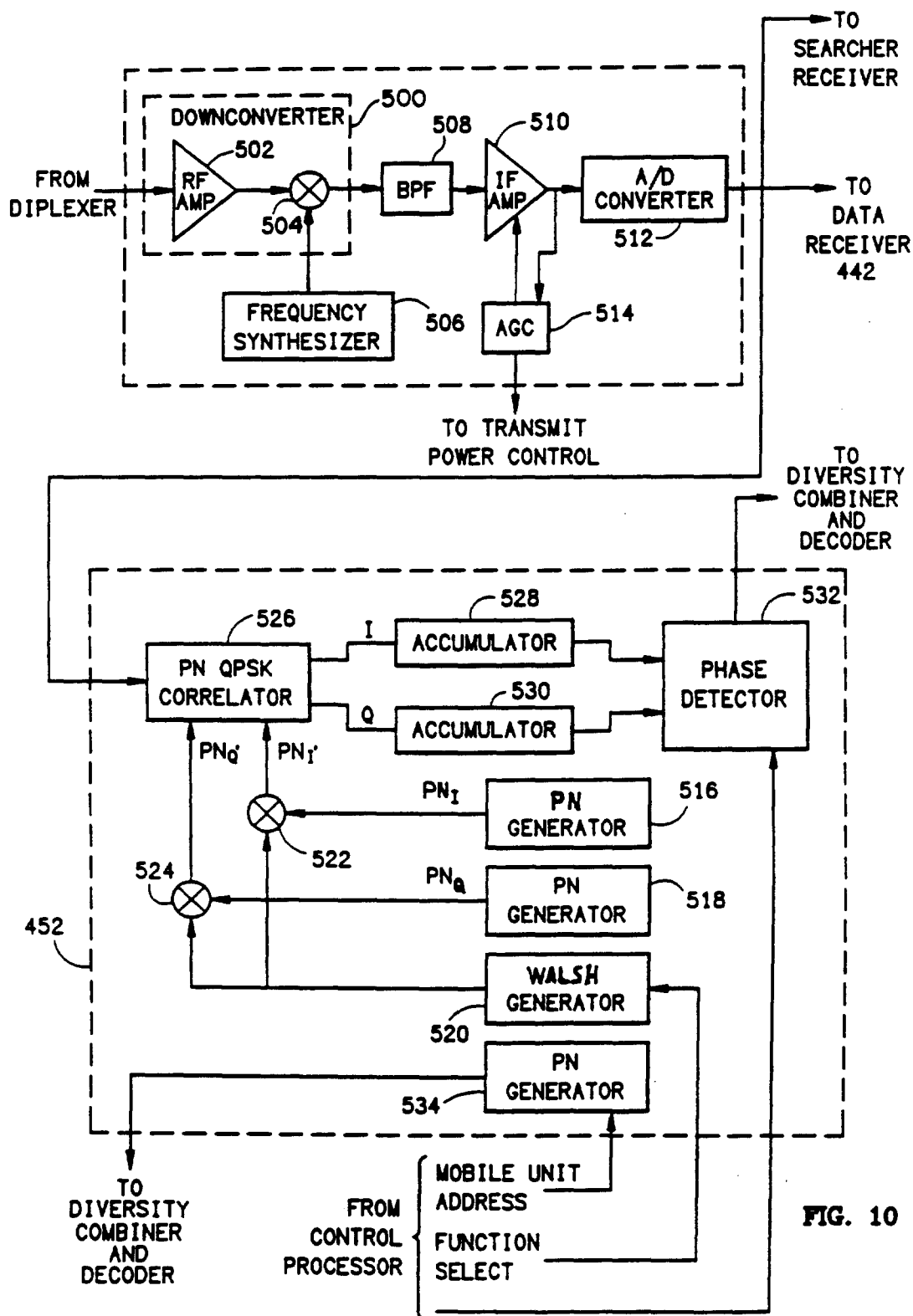


FIG. 10

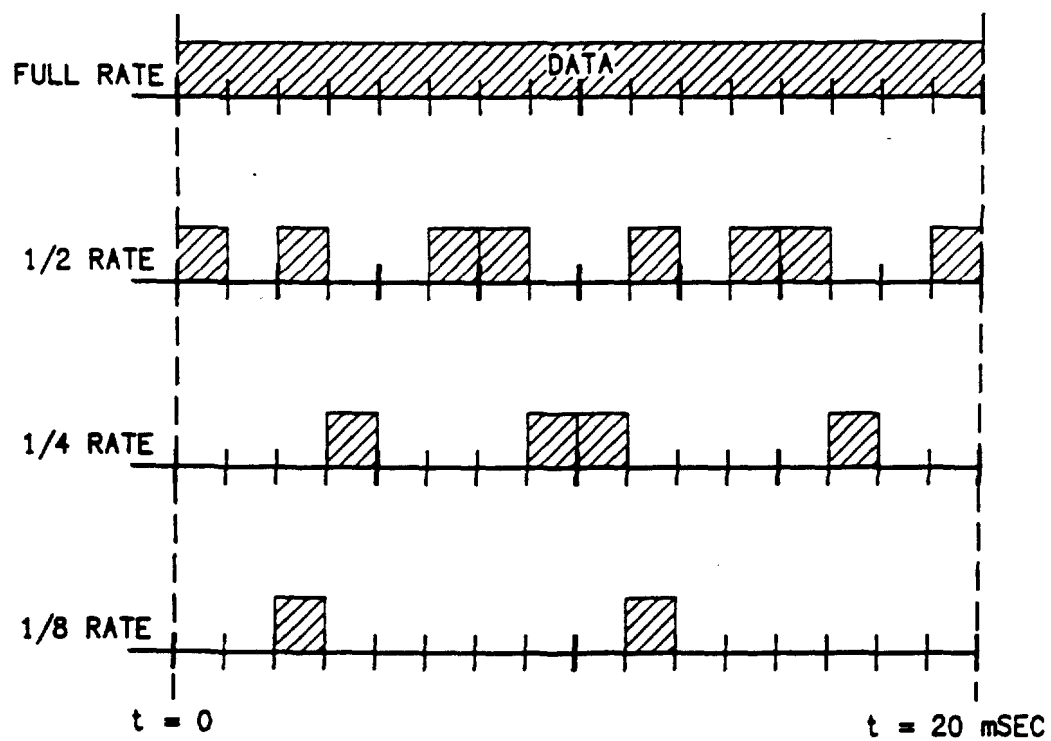
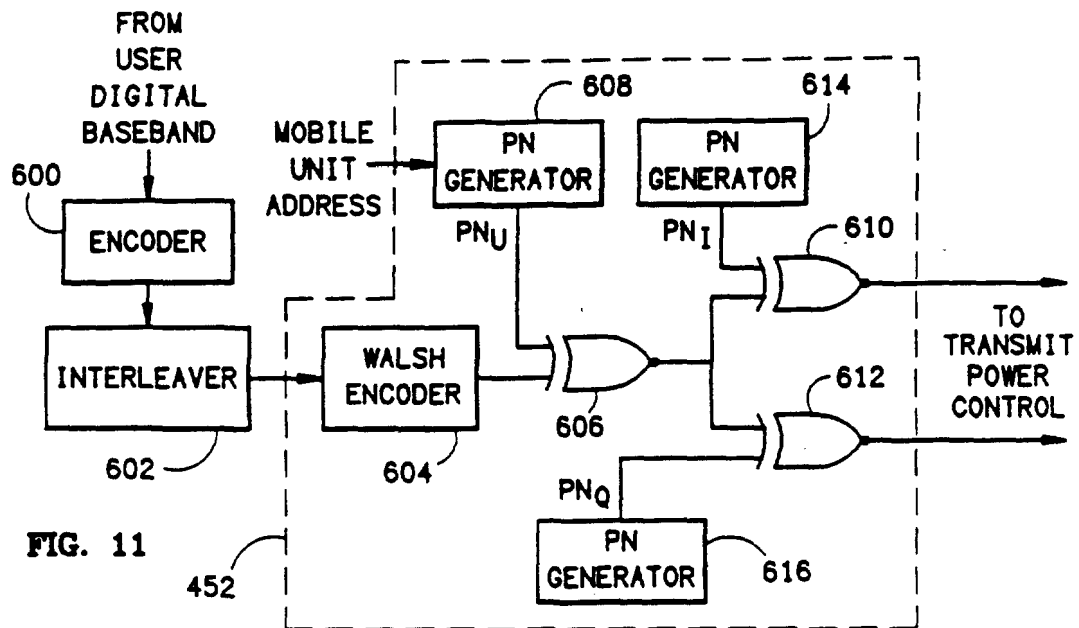


FIG. 12

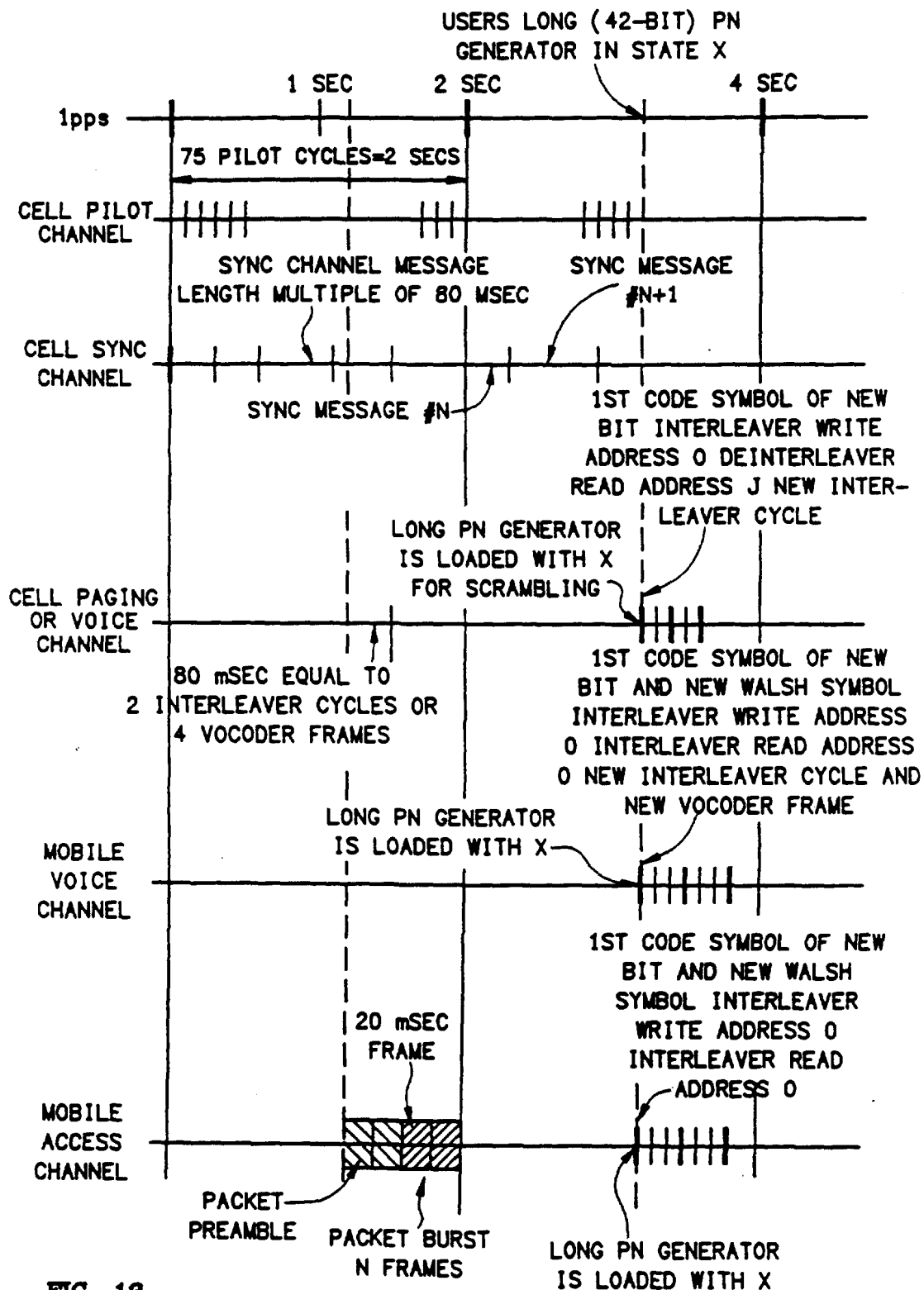


FIG. 13

SYSTEM AND METHOD FOR GENERATING SIGNAL WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM

BACKGROUND OF THE INVENTION

I. Field of the Invention

The present invention relates to cellular telephone systems. More specifically, the present invention relates to a novel and improved system and method for communicating information, in a mobile cellular telephone system or satellite mobile telephone system, using spread spectrum communication signals.

II. Description of the Related Art

The use of code division multiple access (CDMA) modulation techniques is one of several techniques for facilitating communications in which a large number of system users are present. Other multiple access communication system techniques, such as time division multiple access (TDMA), frequency division multiple access (FDMA) and AM modulation schemes such as amplitude companded single sideband (ACSSB) are known in the art. However the spread spectrum modulation technique of CDMA has significant advantages over these modulation techniques for multiple access communication systems. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Pat. No. 4,901,307, issued Feb. 13, 1990, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS", assigned to the assignee of the present invention, of which the disclosure thereof is incorporated by reference.

In the just mentioned patent, a multiple access technique is disclosed where a large number of mobile telephone system users each having a transceiver communicate through satellite repeaters or terrestrial base stations (also referred to as cell-sites stations, cell-sites or for short, cells) using code division multiple access (CDMA) spread spectrum communication signals. In using CDMA communications, the frequency spectrum can be reused multiple times thus permitting an increase in system user capacity. The use of CDMA results in a much higher spectral efficiency than can be achieved using other multiple access techniques.

The satellite channel typically experiences fading that is characterized as Rician. Accordingly the received signal consists of a direct component summed with a multiple reflected component having Rayleigh fading statistics. The power ratio between the direct and reflected component is typically on the order of 6-10 dB, depending upon the characteristics of the mobile unit antenna and the environment about the mobile unit.

Contrasting with the satellite channel, the terrestrial channel experiences signal fading that typically consists of the Rayleigh faded component without a direct component. Thus, the terrestrial channel presents a more severe fading environment than the satellite channel in which Rician fading is the dominant fading characteristic.

The Rayleigh fading characteristic in the terrestrial channel signal is caused by the signal being reflected from many different features of the physical environment. As a result, a signal arrives at a mobile unit receiver from many directions with different transmission delays. At the UHF frequency bands usually employed for mobile radio communications, including those of cellular mobile telephone systems, significant phase

differences in signals traveling on different paths may occur. The possibility for destructive summation of the signals may result, with on occasion deep fades occurring.

Terrestrial channel fading is a very strong function of the physical position of the mobile unit. A small change in position of the mobile unit changes the physical delays of all the signal propagation paths, which further results in a different phase for each path. Thus, the motion of the mobile unit through the environment can result in a quite rapid fading process. For example, in the 850 MHz cellular radio frequency band, this fading can typically be as fast as one fade per second per mile per hour of vehicle speed. Fading this severe can be extremely disruptive to signals in the terrestrial channel resulting in poor communication quality. Additional transmitter power can be used to overcome the problem of fading. However, such power increases effect both the user, in excessive power consumption, and the system by increased interference.

The CDMA modulation techniques disclosed in U.S. Pat. No. 4,901,307 offer many advantages over narrow band modulation techniques used in communication systems employing satellite or terrestrial repeaters. The terrestrial channel poses special problems to any communication system particularly with respect to multipath signals. The use of CDMA techniques permit the special problems of the terrestrial channel to be overcome by mitigating the adverse effect of multipath, e.g. fading, while also exploiting the advantages thereof.

In a CDMA cellular telephone system, the same frequency band can be used for communication in all cells. The CDMA waveform properties that provide processing gain are also used to discriminate between signals that occupy the same frequency band. Furthermore the high speed pseudonoise (PN) modulation allows many different propagation paths to be separated, provided the difference in path delays exceed the PN chip duration, i.e. $1/\text{bandwidth}$. If a PN chip rate of approximately 1 MHz is employed in a CDMA system, the full spread spectrum processing gain, equal to the ratio of the spread bandwidth to system data rate, can be employed against paths that differ by more than one microsecond in path delay from the desired path. A one microsecond path delay differential corresponds to differential path distance of approximately 1,000 feet. The urban environment typically provides differential path delays in excess of one microsecond, and up to 10-20 microseconds are reported in some areas.

In narrow band modulation systems such as the analog FM modulation employed by conventional telephone systems, the existence of multiple paths results in severe multipath fading. With wide band CDMA modulation, however, the different paths may be discriminated against in the demodulation process. This discrimination greatly reduces the severity of multipath fading. Multipath fading is not totally eliminated in using CDMA discrimination techniques because there will occasionally exist paths with delayed differentials of less than the PN chip duration for the particular system. Signals having path delays on this order cannot be discriminated against in the demodulator, resulting in some degree of fading.

It is therefore desirable that some form of diversity be provided which would permit a system to reduce fading. Diversity is one approach for mitigating the deleterious effects of fading. Three major types of diversity

exist: time diversity, frequency diversity and space diversity.

Time diversity can best be obtained by the use of repetition, time interleaving, and error detection and coding which is a form of repetition. The present invention employs each of these techniques as a form of time diversity.

CDMA by its inherent nature of being a wideband signal offers a form of frequency diversity by spreading the signal energy over a wide bandwidth. Therefore, frequency selective fading affects only a small part of the CDMA signal bandwidth.

Space or path diversity is obtained by providing multiple signal paths through simultaneous links from a mobile user through two or more cell-sites. Furthermore, path diversity may be obtained by exploiting the multipath environment through spread spectrum processing by allowing a signal arriving with different propagation delays to be received and processed separately. Examples of path diversity are illustrated in copending U.S. patent application entitled "SOFT HANDOFF IN A CDMA CELLULAR TELEPHONE SYSTEM", Ser. No. 07/433,030, filed Nov. 7, 1989, and copending U.S. patent application entitled "DIVERSITY RECEIVER IN A CDMA CELLULAR TELEPHONE SYSTEM", Ser. No. 07/432,552, also filed Nov. 7, 1989, both assigned to the assignee of the present invention.

The deleterious effects of fading can be further controlled to a certain extent in a CDMA system by controlling transmitter power. A system for cell-site and mobile unit power control is disclosed in copending U.S. patent application entitled "METHOD AND APPARATUS FOR CONTROLLING TRANSMISSION POWER IN A CDMA CELLULAR MOBILE TELEPHONE SYSTEM", Ser. No. 07/433,031, filed Nov. 7, 1989, also assigned to the present invention, now U.S. Pat. No. 5,056,109.

The CDMA techniques as disclosed in U.S. Pat. No. 4,901,307 contemplated the use of coherent modulation and demodulation for both directions of the link in mobile-satellite communications. Accordingly, disclosed therein is the use of a pilot carrier signal as a coherent phase reference for the satellite-to-mobile link and the cell-to-mobile link. In the terrestrial cellular environment, however, the severity of multipath fading, with the resulting phase disruption of the channel, precludes usage of coherent demodulation technique for the mobile-to-cell link. The present invention provides a means for overcoming the adverse effects of multipath in the mobile-to-cell link by using noncoherent modulation and demodulation techniques.

The CDMA techniques as disclosed in U.S. Pat. No. 4,901,307 further contemplated the use of relatively long PN sequences with each user channel being assigned a different PN sequence. The cross-correlation between different PN sequences and the autocorrelation of a PN sequence for all time shifts other than zero both have a zero average value which allows the different user signals to be discriminated upon reception.

However, such PN signals are not orthogonal. Although the cross-correlations average to zero, for a short time interval such as an information bit time the cross-correlation follows a binomial distribution. As such, the signals interfere with each other much the same as if they were wide bandwidth Gaussian noise at the same power spectral density. Thus the other user

signals, or mutual interference noise, ultimately limits the achievable capacity.

The existence of multipath can provide path diversity to a wideband PN CDMA system. If two or more paths are available with greater than one microsecond differential path delay, two or more PN receivers can be employed to separately receive these signals. Since these signals will typically exhibit independence in multipath fading, i.e., they usually do not fade together, the outputs of the two receivers can be diversity combined. Therefore a loss in performance only occurs when both receivers experience fades at the same time. Hence, one aspect of the present invention is the provision of two or more PN receivers in combination with a diversity combiner. In order to exploit the existence of multipath signals, to overcome fading, it is necessary to utilize a waveform that permits path diversity combining operations to be performed.

It is therefore an object of the present invention to provide for the generation of PN sequences which are orthogonal so as to reduce mutual interference, thereby permitting greater user capacity, and support path diversity thereby overcoming fading.

SUMMARY OF THE INVENTION

The implementation of spread spectrum communication techniques, particularly CDMA techniques, in the mobile cellular telephone environment therefore provides features which vastly enhance system reliability and capacity over other communication system techniques. CDMA techniques as previously mentioned further enable problems such as fading and interference to be readily overcome. Accordingly, CDMA techniques further promote greater frequency reuse, thus enabling a substantial increase in the number of system users.

The present invention is a novel and improved method and system for constructing PN sequences that provide orthogonality between the users so that mutual interference will be reduced, allowing higher capacity and better link performance. With orthogonal PN codes, the cross-correlation is zero over a predetermined time interval, resulting in no interference between the orthogonal codes, provided only that the code time frames are time aligned with each other.

In an exemplary embodiment, signals are communicated between a cell-site and mobile units using direct sequence spread spectrum communication signals. In the cell-to-mobile link, pilot, sync, paging and voice channels are defined. Information communicated on the cell-to-mobile link channels are, in general, encoded, interleaved, bi-phase shift key (BPSK) modulated with orthogonal covering of each BPSK symbol along with quadrature phase shift key (QPSK) spreading of the covered symbols.

In the mobile-to-cell link, access and voice channels are defined. Information communicated on the mobile-to-cell link channels are, in general, encoded, interleaved, orthogonal signalling along with QPSK spreading.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, objects, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 is a schematic overview of an exemplary CDMA cellular telephone system;

FIG. 2 is a block diagram of the cell-site equipment as implemented in the CDMA cellular telephone system;

FIG. 3 is a block diagram of the cell-site receiver;

FIGS. 4a-4c form a block diagram of the cell-site transmit modulator; and

FIG. 5 is an exemplary timing diagram of sync channel symbol synchronization;

FIG. 6 is an exemplary timing diagram of sync channel timing with orthogonal covering;

FIG. 7 is an exemplary timing diagram of the overall cell-to-mobile link timing;

FIG. 8 is a block diagram of the mobile telephone switching office equipment;

FIG. 9 is a block diagram of the mobile unit telephone configured for CDMA communications in the CDMA cellular telephone system;

FIG. 10 is a block diagram of the mobile unit receiver; and

FIG. 11 is a block diagram of the mobile unit transmit modulator;

FIG. 12 is an exemplary timing diagram of the mobile-to-cell link for the variable data rate with burst transmission; and

FIG. 13 is an exemplary timing diagram of the overall mobile-to-cell link timing.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In a CDMA cellular telephone system, each cell-site has a plurality of modulator-demodulator units or spread spectrum modems. Each modem consists of a digital spread spectrum transmit modulator, at least one digital spread spectrum data receiver and a searcher receiver. Each modem at the cell-site is assigned to a mobile unit as needed to facilitate communications with the assigned mobile unit.

A soft handoff scheme is employed for a CDMA cellular telephone system in which a new cell-site modem is assigned to a mobile unit while the old cell-site modem continues to service the call. When the mobile unit is located in the transition region between the two cell-sites, the call can be switched back and forth between cell-sites as signal strength dictates. Since the mobile unit is always communicating through at least one cell-site modem, fewer disrupting effects to the mobile unit or in service will occur. The mobile unit thus utilizes multiple receivers for assisting in the hand-off process in addition to a diversity function for mitigating the effects of fading.

In the CDMA cellular telephone system, each cell-site transmits a "pilot carrier" signal. Should the cell be divided into sectors, each sector has an associated distinct pilot signal within the cell. This pilot signal is used by the mobile units to obtain initial system synchronization and to provide robust time, frequency and phase tracking of the cell-site transmitted signals. Each cell-site also transmits spread spectrum modulated information, such as cell-site identification, system timing, mobile paging information and various other control signals.

The pilot signal transmitted by each sector of each cell is of the same spreading code but with a different code phase offset. Phase offset allows the pilot signals to be distinguished from one another thus distinguishing originating cell-sites or sectors. Use of the same pilot signal code allows the mobile unit to find system timing

synchronization by a single search through all pilot signal code phases. The strongest pilot signal, as determined by a correlation process for each code phase, is readily identifiable. The identified strongest pilot signal generally corresponds to the pilot signal transmitted by the nearest cell-site. However, the strongest pilot signal is used whether or not it is transmitted by the closest cell-site.

Upon acquisition of the strongest pilot signal, i.e. initial synchronization of the mobile unit with the strongest pilot signal, the mobile unit searches for another carrier intended to be received by all system users in the cell. This carrier, called the synchronization channel, transmits a broadcast message containing system information for use by the mobiles in the system. The system information identifies the cell-site and the system in addition to conveying information which allows the long PN codes, interleaver frames, vocoders and other system timing information used by the mobile unit to be synchronized without additional searching. Another channel, called the paging channel may also be provided to transmit messages to mobiles indicating that a call has arrived for them, and to respond with channel assignments when a mobile initiates a call.

The mobile unit continues to scan the received pilot carrier signal code at the code offsets corresponding to cell-site neighboring sector or neighboring transmitted pilot signals. This scanning is done in order to determine if a pilot signal emanating from a neighboring sector or cell is becoming stronger than the pilot signal first determined to be strongest. If, while in this call inactive mode, a neighbor sector or neighbor cell-site pilot signal becomes stronger than that of the initial cell-site sector or cell-site transmitted pilot signal, the mobile unit will acquire the stronger pilot signals and corresponding sync and paging channel of the new sector or cell-site.

When a call is initiated, a pseudonoise (PN) code address is determined for use during the course of this call. The code address may be either assigned by the cell-site or be determined by prearrangement based upon the identity of the mobile unit. After a call is initiated the mobile unit continues to scan the pilot signal transmitted by the cell-site through which communications are established in addition to pilot signal of neighboring sectors or cells. Pilot signal scanning continues in order to determine if one of the neighboring sector or cell transmitted pilot signals becomes stronger than the pilot signal transmitted by the cell-site the mobile unit is in communication with. When the pilot signal associated with a neighboring cell or cell sector becomes stronger than the pilot signal of the current cell or cell sector, it is an indication to the mobile unit that a new cell or cell sector has been entered and that a handoff should be initiated.

An exemplary telephone system in which the present invention is embodied is illustrated in FIG. 1. The system illustrated in FIG. 1 utilizes spread spectrum modulation techniques in communication between the system mobile units or mobile telephones, and the cell-sites. Cellular systems in large cities may have hundreds of cell-site stations serving hundreds of thousands of mobile telephones. The use of spread spectrum techniques, in particular CDMA, readily facilitates increases in user capacity in systems of this size as compared to conventional FM modulation cellular systems.

In FIG. 1, system controller and switch 10, also referred to as mobile telephone switching office (MTSO),

typically includes interface and processing circuitry for providing system control to the cell-sites. Controller 10 also controls the routing of telephone calls from the public switched telephone network (PSTN) to the appropriate cell-site for transmission to the appropriate mobile unit. Controller 10 also controls the routing of calls from the mobile units, via at least one cell-site, to the PSTN. Controller 10 may connect calls between mobile users via the appropriate cell-sites since the mobile units do not typically communicate directly with one another.

Controller 10 may be coupled to the cell-sites by various means such as dedicated telephone lines, optical fiber links or microwave communication links. In FIG. 1, two such exemplary cell-sites 12 and 14 including, along with mobile units 16 and 18 each including a cellular telephone are illustrated. Cell-sites 12 and 14 as discussed herein and illustrated in the drawings are considered to service an entire cell. However it should be understood that the cell may be geographically divided into sectors with each sector treated as a different coverage area. Accordingly, handoffs are made between sectors of a same cell as is described herein for multiple cells, while diversity may also be achieved between sectors as is for cells.

In FIG. 1, arrowed lines 20a-20b and 22a-22b respectively define the possible communication links between cell-site 12 and mobile unit 16 and 18. Similarly, arrowed lines 24a-24b and 26a-26b respectively define the possible communication links between cell-site 14 and mobile units 16 and 18. Cell-sites 12 and 14 nominally transmit using equal power.

The cell-site service areas or cells are designed in geographic shapes such that the mobile unit will normally be closest to one cell-site, and within one cell sector should the cell be divided into sectors. When the mobile unit is idle, i.e. no calls in progress, the mobile unit constantly monitors the pilot signal transmissions from each nearby cell-site, and if applicable from a single cell-site in which the cell is sectorized. As illustrated in FIG. 1, the pilot signals are respectively transmitted to mobile unit 16 by cell-sites 12 and 14 upon outbound or forward communication links 20a and 26a. Mobile unit 16 can determine which cell it is in by comparing signal strength in pilot signals transmitted from cell-sites 12 and 14.

In the example illustrated in FIG. 1, mobile unit 16 may be considered closest to cell-site 12. When mobile unit 16 initiates a call, a control message is transmitted to the nearest cell-site, cell-site 12. Cell-site 12 upon receiving the call request message, transfers the called number to system controller 10. System controller 10 then connects the call through the PSTN to the intended recipient.

Should a call be initiated within the PSTN, controller 10 transmits the call information to all the cell-sites in the area. The cell-sites in return transmit a paging message within each respective coverage area that is intended for the called recipient mobile user. When the intended recipient mobile unit hears the page message, it responds with a control message that is transmitted to the nearest cell-site. This control message signals the system controller that this particular cell-site is in communication with the mobile unit. Controller 10 then routes the call through this cell-site to the mobile unit. Should mobile unit 16 move out of the coverage area of the initial cell-site, cell-site 12, an attempt is made to

continue the call by routing the call through another cell-site.

With respect to cellular telephone systems, The Federal Communications Commission (FCC) has allocated a total of 25 MHz for mobile-to-cell links and 25 MHz for cell-to-mobile links. The FCC has divided the allocation equally between two service providers, one of which is the wireline telephone company for the service area and the other chosen by lottery. Because of the order in which allocations were made, the 12.5 MHz allocated to each carrier for each direction of the link is further subdivided into two sub-bands. For the wireline carriers, the sub-bands are each 10 MHz and 2.5 MHz wide. For the non-wireline carriers, the sub-bands are each 11 MHz and 1.5 MHz wide. Thus, a signal bandwidth of less than 1.5 MHz could be fit into any of the sub-bands, while a bandwidth of less than 2.5 MHz could be fit into all but one sub-band.

To preserve maximum flexibility in allocating the CDMA technique to the available cellular frequency spectrum, the waveform utilized in the cellular telephone system should be less than 1.5 MHz in bandwidth. A good second choice would be a bandwidth of about 2.5 MHz, allowing full flexibility to the wireline cellular carriers and nearly full flexibility to non-wireline cellular carriers. While using a wider bandwidth has the advantage of offering increased multipath discrimination, disadvantages exist in the form of higher equipment costs and lower flexibility in frequency assignment within the allocated bandwidth.

In a spread spectrum cellular telephone system, such as illustrated in FIG. 1, the preferred waveform design implemented involves a direct sequence pseudonoise spread spectrum carrier. The chip rate of the PN sequence is chosen to be 1.2288 MHz in the preferred embodiment. This particular chip rate is chosen so that the resulting bandwidth, about 1.25 MHz after filtering, is approximately one-tenth of the total bandwidth allocated to one cellular service carrier.

Another consideration in the choice of the exact chip rate is that it is desirable that the chip rate be exactly divisible by the baseband data rates to be used in the system. It is also desirable for the divisor to be a power of two. In the preferred embodiment, the baseband data rate is 9600 bits per second, leading to a choice of 1.2288 MHz, 128 times 9600 for the PN chip rate.

In the cell-to-mobile link, the binary sequences used for spreading the spectrum are constructed from two different types of sequences, each with different properties to provide different functions. There is an outer code that is shared by all signals in a cell or sector that is used to discriminate between multipath signals. The outer code is also used to discriminate between signals transmitted by different cells or sectors to the mobile units. There is also an inner code that is used to discriminate between user signals transmitted by single sector or cell.

The carrier waveform design in the preferred embodiment for the cell-site transmitted signals utilizes a sinusoidal carrier that is quadrature (four phase) modulated by a pair of binary PN sequences that provide the outer code transmitted by a single sector or cell. The sequences are generated by two different PN generators of the same sequence length. One sequence bi-phase modulates the in-phase channel (I Channel) of the carrier and the other sequence bi-phase modulates the quadrature phase (Q Channel) of the carrier. The result-

ing signals are summed to form a composite four-phase carrier.

Although the values of a logical "zero" and a logical "one" are conventionally used to represent the binary sequences, the signal voltages used in the modulation process are +V volts for a logical "one" and -V volts for a logical "zero". To bi-phase modulate a sinusoidal signal, a zero volt average value sinusoid is multiplied by the +V or -V voltage level as controlled by the binary sequences using a multiplier circuit. The resulting signal may then be band limited by passing through a bandpass filter. It is also known in the art to lowpass filter the binary sequence stream prior to multiplying by the sinusoidal signal, thereby interchanging the order of the operations. A quadrature modulator consists of two bi-phase modulators each driven by a different sequence and with the sinusoidal signals used in the bi-phase modulators having a 90° phase shift therebetween.

In the preferred embodiment, the sequence length for the transmitted signal carrier is chosen to be 32,768 chips. Sequences of this length can be generated by a modified maximal-length linear sequence generator by adding a zero bit to a length 32,767 chip sequence. The resulting sequence has good cross-correlation and autocorrelation properties. Good cross-correlation and autocorrelation properties are necessary to prevent mutual interference between pilot carriers transmitted by different cells.

A sequence this short in length is desirable in order to minimize acquisition time of the mobile units when they first enter the system without knowledge of system timing. With unknown timing, the entire length of the sequence must be searched to determine the correct timing. The longer the sequence, the longer time the acquisition search will require. Although sequences shorter than 32,768 could be used, it must be understood that as sequence length is reduced, the code processing gain is reduced. As processing gain is reduced, the rejection of multipath interference along with interference from adjacent cells and other sources will also be reduced, perhaps to unacceptable levels. Thus, there is a desire to use the longest sequence that can be acquired in a reasonable time. It is also desirable to use the same code polynomials in all cells so that the mobile unit, not knowing what cell it is in when initially acquiring synchronization, can obtain full synchronization by searching a single code polynomial.

In order to simplify the synchronization process, all the cells in the system are synchronized to each other. In the exemplary embodiment, cell synchronization is accomplished by synchronizing all the cells to a common time reference, the Navstar Global Positioning System satellite navigation system which is itself synchronized to Universal Coordinated Time (UTC).

Signals from different cells are differentiated by providing time offsets of the basic sequences. Each cell is assigned a different time offset of the basic sequences differing from its neighbors. In the preferred embodiment, the 32,768 repetition period is divided into a set of 512 timing offsets. The 512 offsets are spaced 64 chips apart. Each sector of each cell in a cellular system is also assigned a different one of the offsets to use for all its transmissions. If there are more than 512 sectors or cells in the system, then the offsets can be reused in the same manner as frequencies are reused in the present analog FM cellular system. In other designs, a different number than 512 offsets could be used. With reasonable

care in assignment of pilot offsets, it should never be necessary for near neighboring cells to use near neighboring time offsets.

All signals transmitted by a cell or one of the sectors of the cell share the same outer PN codes for the I and Q channels. The signals are also spread with an inner orthogonal code generated by using Walsh functions. A signal addressed to a particular user is multiplied by the outer PN sequences and by a particular Walsh sequence, or sequence of Walsh sequences, assigned by the system controller for the duration of the user's telephone call. The same inner code is applied to both the I and Q channels resulting in a modulation which is effectively bi-phase for the inner code.

It is well known in the art that a set of n orthogonal binary sequences, each of length n, for n any power of 2 can be constructed, see *Digital Communications with Space Applications*, S. W. Golomb et al., Prentice-Hall, Inc, 1964, pp. 45-64. In fact, orthogonal binary sequence sets are also known for most lengths which are multiples of four and less than two hundred. One class of such sequences that is easy to generate is called the Walsh function, also known as Hadamard matrices.

A Walsh function of order n can be defined recursively as follows:

$$W(n) = \begin{bmatrix} W(n/2), W(n/2) \\ W(n/2), W'(n/2) \end{bmatrix}$$

where W' denotes the logical complement of W, and $W(1) = |0|$.

Thus,

$$W(2) = \begin{bmatrix} 0, 0 \\ 0, 1 \end{bmatrix} \text{ and}$$

$$W(4) = \begin{bmatrix} 0, 0, 0, 0 \\ 0, 1, 0, 1 \\ 0, 0, 1, 1 \\ 0, 1, 1, 0 \end{bmatrix}$$

$W(8)$ is as follows:

$$W(8) = \begin{bmatrix} 0, 0, 0, 0, 0, 0, 0, 0 \\ 0, 1, 0, 1, 0, 1, 0, 1 \\ 0, 0, 1, 1, 0, 0, 1, 1 \\ 0, 1, 1, 0, 0, 1, 1, 0 \\ 0, 0, 0, 0, 1, 1, 1, 1 \\ 0, 1, 0, 1, 1, 0, 1, 0 \\ 0, 0, 1, 1, 1, 1, 0, 0 \\ 0, 1, 1, 0, 1, 0, 0, 1 \end{bmatrix}$$

A Walsh sequence is one of the rows of a Walsh function matrix. A Walsh function of order n contains n sequences, each of length n bits.

A Walsh function of order n (as well as other orthogonal functions) has the property that over the interval of n code symbols, the cross-correlation between all the different sequences within the set is zero, provided that the sequences are time aligned with each other. This can be seen by noting that every sequence differs from every other sequence in exactly half of its bits. It should also be noted that there is always one sequence contain-

ing all zeroes and that all the other sequences contain half ones and half zeroes.

Neighboring cells and sectors can reuse the Walsh sequences because the outer PN codes used in neighboring cells and sectors are distinct. Because of the differing propagation times for signals between a particular mobile's location and two or more different cells, it is not possible to satisfy the condition of time alignment required for Walsh function orthogonality for both cells at one time. Thus, reliance must be placed on the outer PN code to provide discrimination between signals arriving at the mobile unit from different cells. However, all the signals transmitted by a cell are orthogonal to each other and thus do not contribute interference to each other. This eliminates the majority of the interference in most locations, allowing a higher capacity to be obtained.

The system further envisions the voice channel to be a variable rate channel whose data rate can be varied from data block to data block with a minimum of overhead required to control the data rate in use. The use of variable data rates reduces mutual interference by eliminating unnecessary transmissions when there is no useful speech to be transmitted. Algorithms are utilized within the vocoders for generating a varying number of bits in each vocoder block in accordance with variations in speech activity. During active speech, the vocoder may produce 20 msec. data blocks containing 20, 40, 80, or 160 bits, depending on the activity of the speaker. It is desired to transmit the data blocks in a fixed amount of time by varying the rate of transmission. It is further desirable not to require signalling bits to inform the receiver how many bits are being transmitted.

The blocks are further encoded by the use of a cyclic redundancy check code (CRCC) which appends to the block an additional set of parity bits which can be used to determine whether or not the block of data has been decoded correctly. CRCC check codes are produced by dividing the data block by a predetermined binary polynomial. The CRCC consists of all or a portion of the remainder bits of the division process. The CRCC is checked in the receiver by reproducing the same remainder and checking to see if the received remainder bits are the same as the regenerated check bits.

In the disclosed invention, the receiving decoder decodes the block as if it contains 160 bits, and then again as if it contains 80 bits, etc. until all possible block lengths have been tried. The CRCC is computed for each trial decoding. If one of the trial decodings results in a correct CRCC, the data block is accepted and passed on to the vocoder for further processing. If no trial decoding produces a valid CRCC, the received symbols are passed on to the system's signal processor where other processing operations can optionally be performed.

In the cell transmitter, the power of the transmitted waveform is varied as the data rate of the block is varied. The highest data rate uses the highest carrier power. When the data rate is lower than the maximum, the modulator, in addition to lowering the power, repeats each encoded data symbol a number of times as required to achieve the desired transmission rate. For example, at the lowest transmission rate, each encoded symbol is repeated four times.

In the mobile transmitter, the peak power is held constant but the transmitter is gated off $\frac{1}{2}$, or $\frac{1}{4}$ or $\frac{1}{8}$ of the time in accordance with the number of bits to be

transmitted in the data block. The positions of the on-times of the transmitter is varied pseudo-randomly in accordance with the mobile user's addressed user code.

CELL-TO-MOBILE LINK

In the preferred embodiment, the Walsh function size n , is set equal to sixty-four ($n=64$) for the cell-to-mobile link. Therefore each of up to sixty-four different signals to be transmitted are assigned a unique orthogonal sequence. The forward error correction (FEC) encoded symbol stream for each voice conversation is multiplied by its assigned Walsh sequence. The Walsh coded/FEC encoded symbol stream for each voice channel is then multiplied by the outer PN coded waveform. The resultant spread symbol streams are then added together to form a composite waveform.

The resulting composite waveform is then modulated onto a sinusoidal carrier, bandpass filtered, translated to the desired operating frequency, amplified and radiated by the antenna system. Alternate embodiments of the present invention may interchange the order of some of the just described operations for forming the cell-site transmitted signal. For example, it may be preferred to multiply each voice channel by the outer PN coded waveform and perform the filtering operation prior to summation of all the channel signals to be radiated by the antenna. It is well known in the art that the order of linear operations may be interchanged to obtained various implementation advantages and different designs.

The waveform design of the preferred embodiment for cellular service uses the pilot carrier approach for the cell-to-mobile link as described in U.S. Pat. No. 4,901,307. All cells transmit pilot carriers using the same 32,768 length sequence, but with different timing offsets to prevent mutual interference.

The pilot waveform uses the all-zero Walsh sequence, i.e., a Walsh sequence comprised of all zeroes that is found in all Walsh function sets. The use of all-zero Walsh sequence for all cells' pilot carriers allows the initial search for the pilot waveform to ignore the Walsh functions until after the outer code PN synchronization has been obtained. The Walsh framing is locked to the PN code cycle by virtue of the length of the Walsh frame being a factor of the PN sequence length. Therefore, provided that the cell addressing offsets of the PN code are multiples of sixty-four chips (or the Walsh frame length) then the Walsh framing is known implicitly from the outer PN code timing cycle.

All the cells in a service area are supplied with accurate synchronization. In the preferred embodiment, a GPS receiver at each cell synchronizes the local waveform timing to Universal Coordinated Time (UTC). The GPS system allows time synchronization to better than 1 microsecond accuracy. Accurate synchronization of cells is desirable in order to allow easy handoff of calls between cells when mobiles move from one cell to another with a call in progress. If the neighboring cells are synchronized, the mobile unit will not have difficulty synchronizing to the new cell thereby facilitating a smooth handoff.

The pilot carrier is transmitted at a higher power level than a typical voice carrier so as to provide greater signal to noise and interference margin for this signal. The higher power level pilot carrier enables the initial acquisition search to be done at high speed and to make possible a very accurate tracking of the carrier phase of the pilot carrier by a relatively wide bandwidth phase tracking circuit. The carrier phase obtained from

tracking the pilot carrier is used as the carrier phase reference for demodulation of the carriers modulated by user information signals. This technique allows many user carriers to share the common pilot signal for carrier phase reference. For example, in a system transmitting a total of fifteen simultaneous voice carriers, the pilot carrier might be allocated a transmit power equal to four voice carriers.

In addition to the pilot carrier, another carrier intended to be received by all system users in the cell is transmitted by the cell-site. This carrier, called the synchronization channel, also uses the same 32,768 length PN sequence for spectrum spreading but with a different, pre-assigned Walsh sequence. The synchronization channel transmits a broadcast message containing system information for use by the mobiles in the system. The system information identifies the cell-site and the system and conveys information allowing the long PN codes used for mobile information signals to be synchronized without additional searching.

Another channel, called the paging channel may be provided to transmit messages to mobiles indicating that a call has arrived for them, and to respond with channel assignments when a mobile initiates a call.

Each voice carrier transmits a digital representation of the speech for a telephone call. The analog speech waveform is digitized using standard digital telephone techniques and then compressed using a vocoding process to a data rate of approximately 9600 bits per second. This data signal is then rate $r = \frac{1}{2}$, constraint length $K = 9$ convolutional encoded, with repetition, and interleaved in order to provide error detection and correction functions which allow the system to operate at a much lower signal-to-noise and interference ratio. Techniques for convolutional encoding, repetition and interleaving are well known in the art.

The resulting encoded symbols are multiplied by an assigned Walsh sequence and then multiplied by the outer PN code. This process results in a PN sequence rate of 1.2288 MHz or 128 times the 9600 bps data rate. The resulting signal is then modulated onto an RF carrier and summed with the pilot and setup carriers, along with the other voice carriers. Summation may be accomplished at several different points in the processing such as at the IF frequency, or at the baseband frequency either before or after multiplication by the PN sequence.

Each voice carrier is also multiplied by a value that sets its transmitted power relative to the power of the other voice carriers. This power control feature allows power to be allocated to those links that require higher power due to the intended recipient being in a relatively unfavorable location. Means are provided for the mobiles to report their received signal-to-noise ratio to allow the power to be set at a level so as to provide adequate performance without waste. The orthogonality property of the Walsh functions is not disturbed by using different power levels for the different voice carriers provided that time alignment is maintained.

FIG. 2 illustrates in block diagram from an exemplary embodiment cell-site equipment. At the cell-site, two receiver systems are utilized with each having a separate antenna and analog receiver for space diversity reception. In each of the receiver systems the signals are processed identically until the signals undergo a diversity combination process. The elements within the dashed lines correspond to elements corresponding to the communications between the cell-site and one mo-

bile unit. The output of the analog receivers are also provided to other elements used in communications with other mobile units.

In FIG. 2, the first receiver system is comprised of antenna 30, analog receiver 32, searcher receiver 34 and digital data receiver 36. The first receiver system may also include an optional digital data receiver receiver 38. The second receiver system includes antenna 40, analog receiver 42, searcher receiver 44 and digital data receiver 46.

The cell-site also includes cell-site control processor 48. Control processor 48 is coupled to data receivers 36, 38, and 46 along with searcher receivers 34 and 44. Control processor 48 provides among other functions, functions such as signal processing; timing signal generation; power control; and control over handoff, diversity, diversity combining and system control processor interface with the MTSO (FIG. 8). Walsh sequence assignment along with transmitter and receiver assignment is also provided by control processor 48.

Both receiver systems are coupled by data receivers 36, 38, and 46 to diversity combiner and decoder circuitry 50. Digital link 52 is coupled to receive the output of diversity combiner and decoder circuitry 50. Digital link 52 is also coupled to control processor 48, cell-site transmit modulator 54 and the MTSO digital switch. Digital link 52 is utilized to communicate signals to and from the MTSO (FIG. 8) with cell-site transmit modulator 54 and circuitry 50 under the control of control processor 48.

The mobile unit transmitted signals are direct sequence spread spectrum signals that are modulated by a PN sequence clocked at a predetermined rate, which in the preferred embodiment is 1.2288 MHz. This clock rate is chosen to be an integer multiple of the baseband data rate of 9.6 Kbps.

Signals received on antenna 30 are provided to analog receiver 32. The details of receiver 32 are further illustrated in FIG. 3. Signals received on antenna 30 are provided to downconverter 100 which is comprised of RF amplifier 102 and mixer 104. The received signals are provided as an input to RF amplifier where they are amplified and output to an input to mixer 104. Mixer 104 is provided another input, that being the output from frequency synthesizer 106. The amplified RF signals are translated in mixer 104 to an IF frequency by mixing with the frequency synthesizer output signal.

The IF signals are then output from mixer 104 to bandpass filter (BPF) 108, typically a Surface Acoustic Wave (SAW) filter having a passband of 1.25 MHz, where they are bandpass filtered. The filtered signals are output from BPF 108 to IF amplifier 110 where the signals are amplified. The amplified IF signals are output from IF amplifier 110 to analog to digital (A/D) converter 112 where they are digitized at a 9.8304 MHz clock rate which is exactly 8 times the PN chip rate. Although (A/D) converter 112 is illustrated as part of receiver 32, it could instead be a part of the data and searcher receivers. The digitized IF signals are output from (A/D) converter 112 to data receiver 36, optional data receiver 38 and searcher receiver 34. The signals output from receiver 32 and I and Q channel signals as discussed later. Although as illustrated in FIG. 3 with A/D converter 112 being a single device, with later splitting of the I and Q channel signals, it is envisioned that channel splitting may be done prior to digitizing with two separate A/D converters provided for digitizing the I and Q channels. Schemes for the RF-IF-Base-

band frequency downconversion and analog to digital conversion for I and Q channels are well known in the art.

Searcher receiver 34 is used to at the cell-site to scan the time domain about the received signal to ensure that the associated digital data receiver 36, and data receiver 38 if used, are tracking and processing the strongest available time domain signal. Searcher receiver 64 provides a signal to cell-site control processor 48 which provides control signals to digital data receivers 36 and 38 for selecting the appropriate received signal for processing.

The signal processing in the cell-site data receivers and searcher receiver is different in several aspects than the signal processing by similar elements in the mobile unit. In the inbound, i.e. reverse or mobile-to-cell link, the mobile unit does not transmit a pilot signal that can be used for coherent reference purposes in signal processing at the cell-site. The mobile-to-cell link is characterized by a non-coherent modulation and demodulation scheme using 64-ary orthogonal signalling.

In the 64-ary orthogonal signalling process, the mobile unit transmitted symbols are encoded into one of 2^6 , i.e. 64, different binary sequences. The set of sequences chosen are known as Walsh functions. The optimum receive function for the Walsh function m-ary signal encoding is the Fast Hadamard Transform (FHT).

Referring again to FIG. 2, searcher receiver 34 and digital data receivers 36 and 38, receive the signals output from analog receiver 32. In order to decode the spread spectrum signals transmitted to the particular cell-site receiver through which the mobile unit communicates, the proper PN sequences must be generated. Further details on the generation of the mobile unit signals are discussed later herein.

As illustrated in FIG. 3, receiver 36 includes two PN generators, PN generators 120 and 122, which generate two different short code PN sequences of the same length. These two PN sequences are common to those of all cell-site receivers and all mobile units with respect to the outer code of the modulation scheme as discussed in further detail later herein. PN generators 120 and 122 thus respectively provide the output sequences, PN_I and PN_Q . The PN_I and PN_Q sequences are respectively referred to as the In-Phase (I) and Quadrature (Q) channel PN sequences.

The two PN sequences, PN_I and PN_Q , are generated by different polynomials of degree 15, augmented to produce sequences of length 32,768 rather than 32,767 which would normally be produced. For example, the augmentation may appear in the form of the addition of a single zero to the run of fourteen 0's in a row which appears one time in every maximal-length linear sequence of degree 15. In other words, one state of the PN generator would be repeated in the generation of the sequence. Thus the modified sequence contains one run of fifteen 1's and one run of fifteen 0's.

In the exemplary embodiment receiver 36 also includes a long code PN generator 124 which generates a PN_U sequence corresponding to a PN sequence generated by the mobile unit in the mobile-to-cell link. PN generator 124 can be a maximal-length linear sequence generator that generates a user PN code that is very long, for example degree 42, time shifted in accordance with an additional factor such as the mobile unit address or user ID to provide discrimination among users. Thus the cell-site received signal is modulated by both the long code PN_U sequence and the short code PN_I and

PN_Q sequences. In the alternative, a non-linear encryption generator, such as an encryptor using the data encryption standard (DES) to encrypt a 64-symbol representation of universal time using a user specific key, may be utilized in place of PN generator 124.

The PN_U sequence output from PN generator 124 is exclusive-OR'ed with the PN_I and PN_Q sequences respectively in exclusive-OR gates 126 and 128 to provide the sequences PN_I' and PN_Q' .

The sequences PN_I' and PN_Q' are provided to PN QPSK correlator 130 along with the I and Q channel signals output from receiver 32. Correlator 130 is utilized to correlate the I and Q channel data with the PN_I' and PN_Q' sequences. The correlated I and Q channel outputs of correlator 130 are respectively provided to accumulators 132 and 134 where the symbol data is accumulated over a 4-chip period. The outputs of accumulators 132 and 134 are provided as inputs to Fast Hadamard Transform (FHT) processor 136. FHT processor 148 produces a set of 64 coefficients for every 6 symbols. The 64 coefficients are then multiplied by a weighing function generated in control processor 48. The weighing function is linked to the demodulated signal strength. The weighted data output from FHT 136 is provided to diversity combiner and decoder circuitry 50 (FIG. 2) for further processing.

The second receiver system processes the received signals in a manner similar to that discussed with respect to the first receiver system of FIGS. 2 and 3. The weighted 64 symbols output from receivers 36 and 46 are provided to diversity combiner and decoder circuitry 40. Circuitry 50 includes an adder which adds the weighted 64 coefficients from receiver 36 to the weighted 64 coefficients from receiver 46. The resulting 64 coefficients are compared with one another in order to determine the largest coefficient. The magnitude of the comparison result, together with the identity or the largest of the 64 coefficients, is used to determine a set of decoder weights and symbols for use within a Viterbi algorithm decoder implemented in circuitry 50.

The Viterbi decoder contained within circuitry 50 is of a type capable of decoding data encoded at the mobile unit with a constraint length $K=9$, and of a code rate $r=1/2$. The Viterbi decoder is utilized to determine the most likely information bit sequence. Periodically, nominally 1.25 msec, a signal quality estimate is obtained and transmitted as a mobile unit power adjustment command along with data to the mobile unit. Further information on the generation of this quality estimate is discussed in further detail in the copending application mentioned above. This quality estimate is the average signal-to-noise ratio over the 1.25 msec interval.

Each data receiver tracks the timing of the received signal it is receiving. This is accomplished by the well known technique of correlating the received signal by a slightly early local reference PN and correlating the received signal with a slightly late local reference PN. The difference between these two correlations will average to zero if there is no timing error. Conversely, if there is a timing error, then this difference will indicate the magnitude and sign of the error and the receiver's timing is adjusted accordingly.

The cell-site further includes antenna 62 which is coupled to GPS receiver 64. GPS receiver processes signals received on antenna 62 from satellites in the Navstar Global Positioning System satellite navigation system so as to provide timing signals indicative of

Universal Coordinated Time (UTC). GPS receiver 64 provides these timing signals to control processor 48 for timing synchronizing at the cell-site as discussed previously.

In FIG. 2 optional digital data receiver 38 may be included for improved performance of the system. The structure and operation of this receiver is similar to that described with reference to the data receivers 36 and 46. Receiver 38 may be utilized at the cell-site to obtain additional diversity modes. This additional data receiver alone or in combination with additional receivers can track and receive other possible delay paths of mobile unit transmitted signals. Optional additional digital data receivers such as receiver 38 provides additional diversity modes which are extremely useful in those cell-sites which are located in dense urban areas where many possibilities for multipath signals occur.

Signals from the MTSO are coupled to the appropriate transmit modulator via digital link 52 under control of control processor 48. Transmit modulator 54 under control of control processor 48 spread spectrum modulates the data for transmission to the intended recipient mobile unit. Further details with respect to the structure and operation of transmit modulator 54 are discussed below with reference to FIG. 4.

The output of transmit modulator 54 is provided to transmit power control circuitry 56 where under the control of control processor 48 the transmission power may be controlled. The output of circuitry 56 is provided to summer 57 where it is summed with the output of transmit modulator/transmit power control circuits directed to other mobiles in the cell. The output of summer 57 is provided to transmit power amplifier circuitry 58 where output to antenna 60 for radiating to mobile units within the cell service area. FIG. 2 further illustrates pilot/control channel generators and transmit power control circuitry 66. Circuitry 66 under control of control processor generates and power controls the pilot signal, the sync channel, and the paging channel for coupling to circuitry 58 and output to antenna 60.

A block diagram of an exemplary embodiment of the cell-site transmitter is illustrated in FIG. 4. The transmitter includes a pair of PN sequence generators used in generating the outer code. These PN generators generate two different PN sequences, i.e. the PN_I and PN_Q sequences, as was discussed with reference to FIG. 3. However, these PN_I and PN_Q sequences are delayed in time according to the sector or cell address.

In FIG. 4, the transmitter circuitry of FIG. 3 is illustrated in further detail with the pilot, sync, paging and voice channel signals. The transmitter circuitry includes two PN generators, PN generators 196 and 198, which generate the PN_I and PN_Q sequences. PN generators 196 and 198 are responsive to an input signal corresponding to a sector or cell address signal from the control processor so as to provide a predetermined time delay to the PN sequences. These time delayed PN_I and PN_Q sequences again relate respectively to the In-Phase (I) and Quadrature (Q) channels. Although only two PN generators are illustrated for respectively generating the PN_I and PN_Q sequences for the corresponding channels of the cell-site or sector, it should be understood that many other PN generator schemes may be implemented. For example, in a unsectorized cell, a pair of PN generators may be provided for each of the pilot, sync, paging and voice channels to produce, in synchronization, the PN_I and PN_Q sequences used in the outer code. Such a case may be advantageous to avoid distrib-

uting the PN_I and PN_Q sequences throughout a large number of circuits.

In the preferred embodiment, Walsh function encoding of the channel signals is employed as the inner code. In the exemplary numerology as disclosed herein, a total of 64 different Walsh sequences are available with three of these sequences dedicated to the pilot, sync and paging channel functions. In the sync, paging and voice channels, input data is convolutionally encoded and then interleaved as is well known in the art. Furthermore, the convolutional encoded data is also provided with repetition before interleaving as is also well known in the art.

The pilot channel contains no data modulation and is characterized as an unmodulated spread spectrum signal that all of the users of a particular cell-site or sector use for acquisition or tracking purposes. Each cell, or if divided into sectors, each sector has a unique pilot signal. However, rather than using different PN generators for the pilot signals, it is realized that a more efficient way to generate different pilot signals is to use shifts in the same basic sequence. Utilizing this technique a mobile unit sequentially searches the whole sequence and tunes to the offset or shift that produces the strongest correlation. In using this shift of the basic sequence, the shifts must be such that the pilots in adjacent cells or sectors must not interfere or cancel.

The pilot sequence must therefore be long enough that many different sequences can be generated by shifts in the basic sequence to support a large number of pilot signals in the system. Furthermore, the separation or shifts must be great enough to ensure that there is no interference in pilot signals. Accordingly, in a exemplary embodiment of the present invention the pilot sequence length is chosen to be 2^{15} . The sequence is generated started by a sequence $2^{15} - 1$ with an extra 0 appended to the sequence when a particular state is detected. In the exemplary embodiment there are chosen to be 512 different pilot signals with offsets in the basic sequence of 64 chips. However, offsets may be integer multiples of the 64 chip offset with a corresponding reduction in the number of different pilot signals.

In generating the pilot signal, the Walsh "zero" (W_0) sequence which consists of all zeroes is used so as to not modulate the pilot signal, which in essence is the PN_I and PN_Q sequences. The Walsh "zero" (W_0) sequence is therefore multiplied by the PN_I and PN_Q sequences in exclusive-OR gates. The resulting pilot signal thus contains only the PN_I and PN_Q sequences. With all cell-sites and sectors having the same PN sequence for the pilot signal, the distinguishing feature between cell-sites or sectors of origination of the transmission is the phase of the sequence.

With respect to the portion of transmit modulator and power control circuitry 66 for the pilot channel, Walsh generator (W_0) 200 generates a signal corresponding to the all zero function as just discussed. The timing in the generation of the Walsh function is provided by the control processor, as in the case of all Walsh function generators in the cell-site and mobile unit. The output of generator 200 is provided as an input to both of exclusive-OR gates 202 and 204. The other input of exclusive-OR gate 202 receives the PN_I signal while the other input of exclusive-OR gate 204 receives the PN_Q signal. The PN_I and PN_Q signals are respectively exclusive-OR'ed with the output of generator 200 and respectively provided as inputs to Finite Impulse Re-

sponse (FIR) filters 206 and 208. The filtered signals output from FIR filters 206 and 208 provided to a transmit power control circuitry comprised of gain control elements 210 and 212. The signals provided to gain control elements 210 and 212 are gain controlled in response to input signals (not shown) from the control processor. The signals output from gain control elements are provided to transmit power amplifier circuitry 58 whose detailed structure and function is described later herein.

The sync channel information is encoded and then multiplied in exclusive-OR gates by a preassigned Walsh sequence. In the exemplary embodiment, the selected Walsh function is the (W_{32}) sequence which consists of a sequence of 32 "ones" followed by 32 "zeros". The resulting sequence is then multiplied by the PN_I and PN_Q sequences in exclusive-OR gates. In the exemplary embodiment the sync channel data information is provided to the transmit modulator typically at a rate of 1200 bps. In the exemplary embodiment the sync channel data is preferably convolutionally encoded at a rate $r = \frac{1}{2}$ with a constraint length $K = 9$, with each code symbol repeated twice. This encoding rate and constraint length is common to all encoded forward link channels, i.e. sync, paging and voice. In an exemplary embodiment, a shift register structure is employed for the generators of the code $G_1 = 753$ (octal) and $G_2 = 561$ (octal). The symbol rate to the sync channel is in the exemplary embodiment 4800 sps, i.e. one symbol is 208 μ sec or 256 PN chips.

The code symbols are interleaved by means of a convolutional interleaver spanning in the exemplary embodiment 40 msec. The tentative parameters of the interleaver are $I = 16$ and $J = 48$. Further details on interleaving is found in *Data Communication, Networks and Systems*, Howard W. Sams & Co., 1987, pp. 343-352. The effect of the convolutional interleaver is to disperse unreliable channel symbols such that any two symbols in a contiguous sequence of $I - 1$ or fewer symbols are separated by at least $J + 1$ symbols in a deinterleaver output. Equivalently, any two symbols in a contiguous sequence of $J - 1$ symbols are separated by at least $I + 1$ symbols at the deinterleaver output. In other words, if $I = 16$ and $J = 48$, in a string of 15 symbols, the symbols are transmitted separated by 885 μ sec, thus providing time diversity.

The sync channel symbols of a particular cell or sector are tied to the corresponding pilot signal for that cell or sector. FIG. 5 illustrates the timing of two different pilot channels (N) and (N+1) which are separated by a shift of 64 chips. FIG. 5 illustrates only by way of example a timing diagram for the exemplary pilot and sync channels with the state of the actual pilot signal chips and sync channel symbols not illustrated. Each sync channel starts a new interleaver cycle with the first code symbol (c_x) of a code symbol pair (c_x, c'_x), due to a code repeat of two, shifted with respect to absolute time by an amount equal to the corresponding pilot.

As illustrated in FIG. 5, The N pilot channel starts a new interleaver cycle, or pilot sync, at the time t_x . Similarly, the N+1 pilot channel starts a new interleaver cycle or pilot sync at the time t_y , which occurs 64 chip later in time than time t_x . The pilot cycle in the exemplary embodiment is 26.67 msec long, which corresponds to 128 sync channel code symbols or 32 sync channel information bits. The sync channel symbols are interleaved by a convolutional interleaver which spans 26.67 msec. Thus, when the mobile unit has acquired

the pilot signal, it has immediate sync channel interleaver synchronization.

The sync channel symbols are covered by the preassigned Walsh sequence to provide orthogonality in the signal. In the sync channel, one code symbol spans four cover sequences, i.e. one code symbol to four repetitions of the "32 one"- "32 zero" sequence, as illustrated in FIG. 6. As illustrated in FIG. 6, a single logical "one" represents the occurrence of 32 "one" Walsh chips while a single logical "zero" represents the occurrence of 32 "zero" Walsh chips. Orthogonality in the sync channel is still maintained even though the sync channel symbols are skewed with respect to absolute time depending upon the associated pilot channel because sync channel shifts are integer multiples of the Walsh frame.

The sync channel messages in the exemplary embodiment are variable in length. The length of the message is an integer multiple of 80 msec which corresponds to 3 pilot cycles. Included with the sync channel information bits are cyclic redundancy (CRC) bits for error detection.

FIG. 7 illustrates in the form of a timing diagram the overall exemplary system timing. In the period of two seconds there are 75 pilot cycles. In FIG. 7, the N pilot and sync channels correspond to the sector or cell using the unshifted pilot such that the pilot and sync signals align exactly with UTC time. As such the pilot sync, i.e. initial state, aligns exactly with a common 1 pulse per second (pps) signal.

In all cases in which a shifted pilot is used, a PN phase offset corresponding to the pilot shift is introduced. In other words, pilot sync (initial state) and sync channel messages are skewed with respect to the 1 pps signals. The sync messages carries this phase offset information so that the mobile unit can adjust its timing accordingly.

As soon as a sync channel message has been correctly received, the mobile unit has the ability to immediately synchronize to either a paging channel or a voice channel. At pilot sync, corresponding to the end of each sync message, a new 40 msec interleaver cycle begins. At that time, the mobile unit starts deinterleaving the first code symbol of either a code repetition, or a (c_x, c'_x) pair, with decoder synchronization achieved. The deinterleaver write address is initialized to 0 and the read address is initialized to J, memory deinterleaver synchronization is achieved.

The sync channel messages carry information regarding the state of a 42-bit long PN generator for the voice channel assigned for the communication with the mobile unit. This information is used at the mobile unit digital data receivers to synchronize the corresponding PN generators. For example, in FIG. 7 the sync channel message N+1 contains a 42-bit field which is indicative of the state, state X, that the sector or cell voice channel corresponding long code PN generator will have at a predetermined later time, such as 160 msec later. The mobile unit, after successfully decoding a sync channel message, loads at the correct instant of time the long code PN generator with the state X. The mobile unit long code PN generator is thus synchronized to permit descrambling of the user intended messages.

With respect to the portion of transmit modulator and power control circuitry 66 for the sync channel, the sync channel information is input from the control processor to encoder 214. The sync channel data in the exemplary embodiment is, as discussed above, convolutionally encoded by encoder 214. Encoder 214 further

provides repetition of the encoded symbols, in the case of the sync channel the encoded symbols are repeated. The symbols output from encoder 214 are provided to interleaver 215 which provides convolutional interleaving of the symbols. The interleaved symbols output from interleaver 215 are provided as an input to exclusive-OR gate 216.

Walsh generator 218 generates a signal corresponding to the Walsh (W_{32}) sequence that is provided as the other input to exclusive-OR gate 216. The sync channel symbol stream and the Walsh (W_{32}) sequence are exclusive-OR'ed by exclusive-OR gate 216 with the result thereof provided as an input to both of exclusive-OR gates 220 and 222.

The other input of exclusive-OR gate 220 receives the PN_I signal while the other input of exclusive-OR gate 222 receives the PN_Q signal. The PN_I and PN_Q signals are respectively exclusive-OR'ed with the output of exclusive-OR gate 218 and respectively provided as inputs to Finite Impulse Response (FIR) filters 224 and 226. The filtered signals output from FIR filters 224 and 226 provided to a transmit power control circuitry comprised of digital variable gain control elements 228 and 230. The signals provided to gain control elements 228 and 230 are digitally gain controlled in response to input digital signals (not shown) from the control processor. The signals output from gain control elements 228 and 230 are provided to transmit power amplifier circuitry 58.

The paging channel information is also encoded with repetition, interleaved and then multiplied by a preassigned Walsh sequence. The resulting sequence is then multiplied by the PN_I and PN_Q sequences. The data rate of the paging channel for a particular sector or cell is indicated in an assigned field in the sync channel message. Although the paging channel data rate is variable, it is in the exemplary embodiment fixed for each system at one of the following exemplary data rates: 9.6, 4.8, 2.4 and 1.2 kbps.

With respect to the transmit modulator and power control circuitry of the paging channel, the paging channel information is input from the control processor to encoder 232. Encoder 232 is in the exemplary embodiment a convolutional encoder that also provides repetition of the symbols according to the assigned data rate of the channel. The output of encoder 232 is provided to interleaver 233 where the symbols are convolutional interleaved. The output from interleaver 233 is provided as an input to exclusive-OR gate 234. Although the paging channel data rate will vary, the code symbol rate is kept constant at 19.2 kbps by code repetition.

Walsh generator 236 generates a signal, corresponding to a preassigned Walsh sequence, that is provided as the other input to exclusive-OR gate 234. The symbol data and Walsh sequence are exclusive-OR'ed by exclusive-OR gate 234 and provided as an input to both of exclusive-OR gates 238 and 240.

The other input of exclusive-OR gate 238 receives the PN_I signal while the other input of exclusive-OR gate 240 receives the PN_Q signal. The PN_I and PN_Q signals are respectively exclusive-OR'ed with the output of exclusive-OR gate 234 and respectively provided as inputs to Finite Impulse Response (FIR) filters 242 and 244. The filtered signals output from FIR filters 242 and 244 are provided to a transmit power control circuitry comprised of gain control elements 246 and 248. The signals provided to gain control elements 246 and 248

are gain controlled in response to input signals (not shown) from the control processor. The signals output from gain control elements are provided to transmit power amplifier circuitry 58.

The data of each voice channel is also encoded with repetition, interleaved, scrambled, multiplied by its assigned Walsh sequence (W_i), and then multiplied by the PN_I and PN_Q sequences. The Walsh sequence to be used by a particular channel is assigned by the system controller at call setup time in the same manner as channels are assigned to calls in the analog FM cellular system. In the exemplary embodiment illustrated herein, up to 61 different Walsh sequences are available for use by the voice channels.

In the exemplary embodiment of the present invention, the voice channel utilizes a variable data rate. The intent in using a variable data rate is to lower the data rate when there is no voice activity thereby reducing interference generated by this particular voice channel to other users. The vocoder envisioned to provide variable rate data is disclosed in copending U.S. patent application "VARIABLE RATE VOCODER" Ser. No. 07/713,661, filed June 11, 1991, also assigned to the assignee of the present invention. Such a vocoder produces data at four different data rates based on voice activity on a 20 msec frame basis. Exemplary data rates are 9.6 kbps, 4.8 kbps, 2.4 kbps and 1.2 kbps. Although the data rate will vary on a 20 msec basis, the code symbol rate is kept constant by code repetition at 19.2 kbps. Accordingly, the code symbols are repeated 2, 4 and 8 times for the respective data rates 4.8 kbps, 2.4 kbps and 1.2 kbps.

Since the variable rate scheme is devised to reduce interference, the code symbols at the lower rates will have lower energy. For example, for the exemplary data rates of 9.6 kbps, 4.8 kbps, 2.4 kbps and 1.2 kbps, the code symbol energy (E_s) is respectively $E_b/2$, $E_b/4$, $E_b/8$ and $E_b/16$ where E_b is the information bit energy for the 9.6 kbps transmission rate.

The code symbols are interleaved by a convolutional interleaver such that code symbols with different energy levels will be scrambled by the operation of the interleaver. In order to keep track of what energy level a code symbol should have a label is attached to each symbol specifying its data rate for scaling purposes. After orthogonal Walsh covering and PN spreading, the quadrature channels are digitally filtered by a Finite Impulse Response (FIR) filter. The FIR filter will receive a signal corresponding to the symbol energy level in order to accomplish energy scaling according to the data rate. The I and Q channels will be scaled by factors of: 1, $1/\sqrt{2}$, $1/2$, or $1/2\sqrt{2}$. In one implementation the vocoder would provide a data rate label in the form of a 2-bit number to the FIR filter for controlling the filter scaling coefficient.

In FIG. 4, the circuitry of two exemplary voice channels, voice channels (i) and (j) are illustrated. The voice channel (i) data is input from an associated vocoder (not shown) to transmit modulator 54 (FIG. 3). Transmit modulator 54 is comprised of encoder 250_i, interleaver 251_i, exclusive-OR gates 252_i, 255_i, 256_i and 258_i, PN generator 253_i, and Walsh generator (W_i) 254_i.

The voice channel (i) data is input to encoder 250_i, where in the exemplary embodiment it is convolutional encoded with code symbol repetition according to the input data rate. The encoded data is then provided to interleaver 251_i, where, in the exemplary embodiment, it is convolutional interleaved. Interleaver 251_i also re-

ceives from the vocoder associated with the voice channel (i) a 2-bit data rate label that is interleaved with the symbol data to identify at the data rate to the FIR filters. The data rate label is not transmitted. At the mobile unit, the decoder checks for all possible codes. The interleaved symbol data is output from interleaver 251, at an exemplary rate of 19.2 kbps to an input of exclusive-OR gate 252.

In the exemplary embodiment, each voice channel signal is scrambled to provide greater security in cell-to-mobile transmissions. Although such scrambling is not required it does enhance the security in communications. For example, scrambling of the voice channel signals may be accomplished by PN coding the voice channel signals with a PN code determined by the mobile unit address of user ID. Such scrambling may use the PN_U sequence or encryption scheme as discussed with reference to FIG. 3 with respect to the particular receiver for the mobile-to-cell communications. Accordingly, a separate PN generator may be implemented for this function as illustrated in FIG. 4. Although scrambling is discussed with reference to a PN sequence, scrambling may be accomplished by other techniques including those well known in the art.

Referring again to FIG. 4, scrambling of the voice channel (i) signal may be accomplished by providing PN generator 253, which receives the assigned mobile unit address from the control processor. PN generator 253 generates a unique PN code that is provided as the other input to exclusive-OR gate 252. The output of exclusive-OR gate 252 is instead provided to the one input of exclusive-OR gate 255.

Walsh generator (W_i) 254 generates, in response to a function select signal and timing signals from the control processor, a signal corresponding to a preassigned Walsh sequence. The value of the function select signal may be determined by the address of the mobile unit. The Walsh sequence signal is provided as the other input to exclusive-OR gate 255. The scrambled symbol data and Walsh sequence are exclusive-OR'ed by exclusive-OR gate 255, with the result provided as an input to both of exclusive-OR gates 256 and 258. PN generator 253, along with all other PN generators and Walsh generators at the cell-site provide an output at 1.2288 MHz. It should be noted that PN generator 253 includes a decimator which provides an output at a 19.2 kHz rate to exclusive-OR gate 255.

The other input of exclusive-OR gate 256 receives the PN_I signal while the other input of exclusive-OR gate 258 receives the PN_Q signal. The PN_I and PN_Q signals are respectively exclusive-OR'ed with the output of exclusive-OR gate 252 and respectively provided as inputs to Finite Impulse Response (FIR) filters 260 and 262. The input symbols are filtered according to the input data rate label (not shown) from convolutional interleaver 251. The filtered signals output from FIR filters 260 and 262, provided to a portion of transmit power control circuitry 56 comprised of gain control elements 264 and 266. The signals provided to gain control elements 264 and 266 are gain controlled in response to input signals (not shown) from the control processor. The signals output from gain control elements are provided to transmit power amplifier circuitry 58.

In addition to voice bits, the forward link voice channel carries power control information. The power control bit rate is in the exemplary embodiment 800 bps. The cell-site receiver which is demodulating the mo-

bile-to-cell signal from a given mobile, generates the power control information which is inserted in the cell-to-mobile voice channel addressed to that particular mobile. Further details on the power control feature is disclosed in the above identified copending application.

Power control bits are inserted at the output of the convolutional interleaver by means of a technique called code symbol puncturing. In other words, whenever a power control bit needs to be transmitted two code symbols are replaced by two identical code symbols with polarity given by the power control information. Moreover, power control bits are transmitted at the energy level corresponding to the 9600 bps bit rate.

An additional constraint imposed on the power control information stream is that the position of the bits must be randomized among mobile-to-cell channels. Otherwise the full energy power control bits would generate spikes of interference at regular intervals, thus diminishing the detectability of such bits.

FIG. 4 further illustrates voice channel (j) which is identical in function and structure to that of voice channel (i). It is contemplated that there exist many more voice channels (not illustrated) with the total of voice channel being up to 61 for the illustrated embodiment.

With respect to the Walsh generators of FIG. 4, Walsh functions are a set of orthogonal binary sequences that can be easily generated by means well known in the art. The characteristic of interest in the Walsh function is that each of the 64 sequences is perfectly orthogonal to all of the other sequences. As such, any pair of sequences differ in exactly as many bit positions as they agree, i.e. 32 over an interval of 64 symbols. Thus when information is encoded for transmission by the Walsh sequences the receiver will be able to select any one of the Walsh sequences as a desired "carrier" signal. Any signal energy encoded onto the other Walsh sequences will be rejected and not result in mutual interference to the desired one Walsh sequence.

In the exemplary embodiment for the cell-to-mobile link, the sync, paging and voice channels as mentioned previously use convolutional encoding of a constraint length $K=9$ and code rate $r=1/2$, that is, two encoded symbols are produced and transmitted for every information bit to be transmitted. In addition to the convolutional encoding, convolutional interleaving of symbol data is further employed. It is further envisioned that repetition is also utilized in conjunction with the convolutional encoding. At the mobile unit the optimum decoder for this type of code is the soft decision Viterbi algorithm decoder. A standard design can be used for decoding purposes. The resulting decoded information bits are passed to the mobile unit digital baseband equipment.

Referring again to FIG. 4, circuitry 58 includes series of digital to analog (D/A) converters for converting the digital information from the PN_I and PN_Q spread data for the pilot, sync, paging and voice channels to analog form. In particular the pilot channel PN_I spread data is output from gain control element 210 to D/A converter 268. The digitized data is output from D/A converter 268 to a summer 284. Similarly, the output of the corresponding gain control elements for the sync, paging and voice channels PN_I spread data, i.e. gain control elements 228, 246, and 264i-264j, are respectively provided to D/A converters 272, 276 and 280i-280j where the signals are digitized and provided to summer 284. The PN_Q spread data for the pilot, sync, paging and voice channels are output from gain control elements